

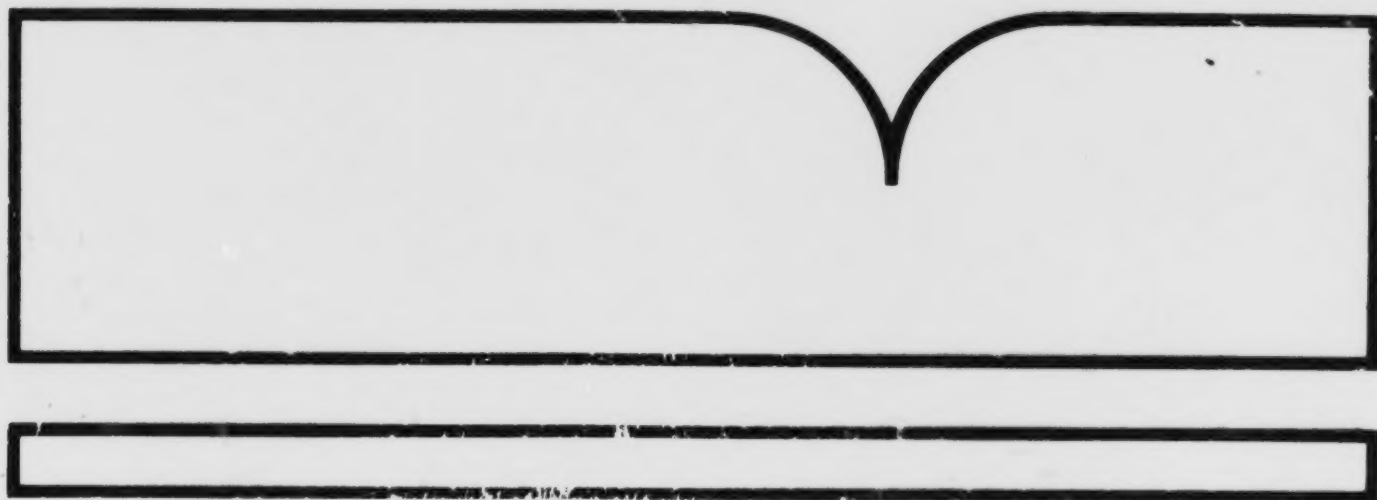
Biologically Mediated Corrosion and
Water Quality Deterioration in
Distribution Systems

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16. ABSTRACT This project was designed to evaluate biologically mediated corrosion and changes in water quality in municipal water distribution systems. Methods employed included a national questionnaire survey, analysis of field samples and laboratory studies. The questionnaire confirmed the vast majority of all utilities surveyed had water quality problems related to the distribution system. Actual analysis of selected samples indicated that generally there was an increase in the number of heterotrophic bacteria in samples taken from locations where water quality complaints were numerous. Studies on steel, copper and PVC pipes showed that steel pipes exhibited greater sediment accumulation, but the number of bacteria per unit area of pipe surface was essentially the same for all three pipe systems. Batch culture corrosion studies indicated that dissolved oxygen was the most important parameter affecting the corrosion rate of cast iron. The addition of microorganisms isolated from pipe loop systems increased the rate of corrosion. The presence of microorganisms resulted in more localized pitting of the pipe.		
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BIOLOGICALLY MEDIATED CORROSION
AND WATER QUALITY DETERIORATION
IN DISTRIBUTION SYSTEMS

by

John T. O'Connor and Shankha K. Banerji
University of Missouri-Columbia
Columbia, Missouri 65211

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Project Officer

Raymond Taylor
Drinking Water Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communications link between the researcher and the user community.

The present study attempts to define the problem of water quality deterioration in water distribution systems. The distribution system is the last link in the complex chain which brings drinking water to the American people. Until recently, the diversity of microbial growth in such systems and the chemical changes caused by their activity were generally unknown. The information presented in this report provides a more scientific basis for dealing with problems of corrosion and water quality deterioration in water distribution systems.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

Studies were conducted to evaluate biologically mediated corrosion and deterioration of water quality in municipal water distribution systems. The project included (1) a national questionnaire survey of water utilities, (2) an evaluation of five Missouri water supply systems, (3) a 1-year study of nine water distribution systems across the country, (4) fabrication of a pipe manifold system to monitor and study water quality changes and microbiological growths in the laboratory, (5) construction of a laboratory-scale pipe loop system to study water quality changes and corrosion, (6) corrosion studies in batch reactor systems, and (7) an evaluation of corrosion control using polyphosphate.

The national questionnaire survey indicated that regardless of water supply source, utility size, or geographical location, virtually every responding utility experienced some water quality problem in its distribution system.

Evaluation of five Missouri water supply systems indicated that the most frequently observed water quality changes were loss of chlorine residuals, depletion of dissolved oxygen, increase in iron concentrations, and the occasional presence of hydrogen sulfide. Higher bacterial plate counts were generally observed in locations where water quality complaints were more numerous.

Selective enrichment culture techniques yielded many different microorganisms in distribution system waters. These included sulfate-reducing, sulfur-oxidizing, iron-precipitating, nitrogen-fixing, nitrifying, denitrifying and stalk-producing microorganisms.

A 1-year study of nine water distribution systems located across the country confirmed some of the observations made in the water supply studies in Missouri. In several instances, the data showed no correlation between chlorine residuals (free or combined) and standard plate counts (SPC). In some instances, atypical coliform colonies were observed on membrane filter plates from distribution system samples. The modified standard plate count technique with diluted media (1:2),

incubation temperature of 20° to 25°C and incubation periods of 6 to 8 days yielded higher plate counts than those obtained on R-2A or SPC test media.

Continuous-flow pipe manifold systems were developed to monitor the sediment and biological growth potential of finished water supplies. TOC levels of less than 5 mg/l appeared to limit the biological growth in test manifold tubes. Chlorine residual concentrations of 1 mg/l and greater also limited the amount of biological growth. Dissolved methane at concentrations of 9 to 13 mg/l increased the amount of biological growth in the manifold systems. Steel pipes exhibited greater sediment accumulation than did copper or PVC pipes. These sediments were nonfilterable, inert residues. The number of bacteria per unit surface of pipe was about the same for all three pipe systems, which indicates that the potential for microbially mediated reactions may be similar in all three pipe materials.

Pipe loop systems designed to simulate the water distribution system piping could not be maintained bacteria-free despite repeated disinfection with high doses of chlorine. The pipe loop system supported a variety of microorganisms similar in diversity to those observed in field monitoring of several water distribution systems in Missouri.

From closed-system, stirred-reactor corrosion tests, it was concluded that dissolved oxygen was the most important parameter affecting the rate of corrosion of cast iron test specimens. With the addition of microorganism cultures isolated from the pipe loop system, the corrosion rate of the cast iron specimens was found to increase. Moreover, in the presence of microorganisms, more localized pitting of the cast iron specimens was observed.

Finally, corrosion studies using cast iron test specimens were conducted in the presence and absence of commercial formulations. These products did not effectively decrease corrosion rates in galvanic test systems until a sufficient amount of phosphate (generally greater than 20mg/l as P_2O_5) was added. The corrosion rate of cast iron test specimens in the presence of polyphosphate compounds was reduced by increasing the total alkalinity, pH, and calcium concentrations as well as by decreasing the concentration of dissolved oxygen. The corrosion inhibition resulting from the addition of polyphosphate in galvanic test systems appeared to be due to the formation of a condensed phosphate coating on the cathode (cathodic polarization).

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SECTION 1

INTRODUCTION

In nearly every community in the United States, the quality of treated water pumped into the water distribution mains from the water purification plant is high. Most water utilities provide water that meets federal standards set for drinking waters. But once the water enters the distribution system, some fairly substantial quality changes can occur that the water purveyor cannot readily control.

Virtually every waterworks superintendent is familiar with and sensitive to consumer complaints. Aside from complaints of no water, the most frequently voiced complaints refer to red water, tastes and odors, slimes, and cloudy water. Most of these problems originate in the distribution system. When placed in perspective, the deterioration of water quality in the distribution system may be the single greatest water problem that affects the daily lives of most American consumers. This deterioration in water quality results in common nuisances such as iron staining of laundry and porcelain fixtures, unpleasant tastes and odors, and the presence of suspended debris in drinking water. Often, the debris may be accumulations of bacterial cell mass (slime) plus iron oxides (rust).

In portions of distribution systems where microbiological growths accumulate on the walls of the pipe, a number of chemical changes can occur. The first major change might be the loss of chlorine residual. Thereafter, the respiration of the microorganisms may result in the consumption of oxygen. After some time, the oxygen may be depleted, sometimes to exhaustion. The absence of oxygen in certain areas of the distribution system could then lead to the growth of anaerobic bacteria. These organisms may include those commonly found organisms that reduce nitrate, sulfate, or even organic substances to produce nitrogen, hydrogen sulfide, carbon dioxide or methane. These reduction reactions may, in turn, result in the oxidation of cast iron (corrosion). The subsequent precipitation of the corrosion products yields so-called red water and black water.

The present study of biologically mediated corrosion and deterioration of water quality in water distribution systems had the following objectives:

1. To determine the extent and nature of water quality problems originating in water distribution systems in the U.S.
2. To conduct laboratory studies to assess the potential for a treated water to promote sediment deposition and microbial growth in distribution systems.
3. To determine the role of microorganisms in mediating chemical changes observed in distribution systems.
4. To determine remedial measures for controlling sediment deposition, organism growth, and quality deterioration.
5. To prepare a guideline document for use by water utilities for assessing and controlling water quality problems in distribution systems.

SECTION 2

CONCLUSIONS

The following conclusions were derived from the study:

1. In a survey conducted to determine the extent and nature of water quality problems in distribution systems in the United States, it was found that 60% of the responding utilities (354 utilities) reported taste and odor to be their most common water quality problem. Red water ranked second, with 47.7% of the utilities reporting this problem. Complaints of cloudy and black water were, respectively, the next two most frequently cited water quality problems. These responses indicated that regardless of water source, utility size, or geographical location, virtually every utility periodically experiences some water quality problem that originates in their distribution system.
2. Evaluations of distribution system water quality in five Missouri communities indicate:
 - a. The most frequently observed water quality changes included the loss of chlorine residuals, decreases in dissolved oxygen concentrations, and increases in iron concentrations. Although changes in sulfate ion concentrations were not measureable, increases in hydrogen sulfide were often evident.
 - b. In general, higher bacterial plate counts were observed in locations where consumers reported water quality problems. Higher plate counts were also generally associated with low chlorine residuals.
 - c. A wide variety of microorganisms were isolated from the five distribution systems studied. Selective enrichment culture media yielded sulfate-reducing, sulfur-oxidizing,

iron-precipitating, nitrogen-fixing, nitrifying, denitrifying and stalk-producing microorganisms. These microorganisms belong to groups that can transform carbon, nitrogen, sulfur and iron as part of their microbiotic cycles. Water quality changes can thus be influenced and mediated by the organisms indigenous to these water distribution systems.

3. An additional 1-year study of data from nine water distribution systems throughout the U.S. confirmed some of the observations made from the Missouri water distribution system studies. The systems studied were: Tacoma, Washington; Chicago, Illinois; Springfield, Illinois; Champaign, Illinois; Durham, North Carolina; Columbia, Missouri; Tampa, Florida; Minneapolis, Minnesota; and Sioux Falls, South Dakota.
 - a. No clear relation was observed in the Tacoma, Washington water distribution system between free chlorine residuals and standard plate counts. High SPC values could be observed at low (<0.1 mg/l) as well as high chlorine residuals (up to 0.8 mg/l).
 - b. The City of Chicago, Illinois has infrequent water quality problems in their distribution systems. But occasional high water velocities suspend accumulations and result in complaints of dirty water.
 - c. The primary water quality complaints in Springfield, Illinois were related to taste and odors during spring and fall lake turnovers. Water quality in the distribution system remains good throughout the year except for decreases in chlorine residuals in the peripheral areas. Standard plate count values were quite low throughout the system (<5 /ml).
 - d. Water quality in the Champaign, Illinois water distribution system was also good. There was some decrease in chlorine residuals in the extremities of the system. While five samples had positive coliform counts, there was no relationship evident between this presence of coliform and the amount of chlorine residuals present in the system. In a few samples, non-coliform colonies were observed on membrane filter plates. These non-coliform colonies

were not present when chlorine residuals were low or zero. The SPC values were generally quite low (<42/ml) throughout the system whereas samples from the extremity of the system had high SPC.

- e. Consumer complaints in Durham, North Carolina refer to red water, odor of rotten eggs, and disagreeable tastes. The red water problems appear to be due to corrosion of the mains in many parts of the distribution system. The depletion of chlorine residuals in some water samples are related to high values of SPC and, occasionally, the presence of total coliforms. A definite depletion of dissolved oxygen was observed as the water moved to more distant points in the distribution system.
- f. Distribution water quality problems encountered in Columbia, Missouri include cloudiness and red water. Columbia water quality is quite high and high chlorine residuals can be maintained throughout the system most of the time. Standard plate counts are low except at a few locations. While there was no definite relationship between high SPC and low chlorine residuals, at some locations it was noted that depleted chlorine residuals were associated with higher bacterial counts. Although total coliform counts were always less than one per 100 ml, in many instances, unidentified pink or red atypical coliform colonies were observed on the membrane filter plates. There was no observable relationship between the presence of these pink or red colonies and chlorine residuals throughout the system.
- g. Water quality problems reported in Tampa, Florida included red water and sediments. The microbiological water quality as measured by SPC's appeared directly related to the depletion of chlorine residuals in the system. Chlorine residuals did not persist in the portion of the system supplied by the surface water source. There was some evidence that total iron increases in the system were caused by pipeline corrosion.
- h. The water quality complaints in Minneapolis, Minnesota distribution system were also caused by sediments and, in some isolated areas, rusty water. Dissolved oxygen levels were high, and

combined chlorine residuals persisted throughout the system. Coliform MPN were always less than 2.2 per 100 ml, and SPC's were less than 50 per ml in most of the samples. At 20°C incubation temperature, SPC values were generally higher than those obtained at 35°C.

- i. In the Sioux Falls, South Dakota distribution system, the depletion of chlorine residual in certain areas and high iron concentrations were reported. Analysis of the water quality data indicated that both increases in iron concentrations and concomitant depletions in dissolved oxygen occurred at several locations. There was no clear relationship between chlorine residuals and SPC's.
4. The analyses of hydrant flushing samples from 12 utilities throughout the United States indicated that samples that had low turbidity and low total and volatile solids had few organisms as measured by SPC and on R-2A plates. Samples that were turbid and brown showed positive results for most of the enrichment culture tests. They also exhibited high concentrations of total solids and total iron. Many of the samples showed the presence of sulfate-reducing bacteria. In most samples analyzed, the diluted SPC media developed more colony growth compared with R-2A media.
5. Studies employing a pipe manifold system to simulate a water distribution system indicated the following:
 - a. Microbial growths in pipes are related to TOC levels. TOC levels of 5.0 mg/l and less limit the amount of microbial growth in pipe manifold systems.
 - b. The addition of chlorine reduced the accumulation of microbial growth. Free chlorine residuals of 1.0 mg/l and higher suppressed microbial growth significantly. Chloramine doses in the range of 1 to 2 mg/l were not as effective.
 - c. The presence of methane in source water stimulates microbial growth. Methane concentrations of about 9 to 13 mg/l in the influent increased the amount of microbial growth in the system markedly.

- d. Studies of the effect of pipe materials on the sediment accumulation and biological growth on the pipe surface showed that steel pipes developed the largest amount of attached sediment with time (35 days) compared with PVC or copper pipes. The major portion of the accumulation of steel pipe was non-filterable, inert residue. Despite less accumulation on PVC and copper pipes, bacterial plate count data indicated that there was a comparable number of microorganisms in the sediments of all pipe materials. Therefore the potential for microbially mediated reactions may have been roughly equivalent in all three pipe materials.
 - e. Bacterial plate counts on accumulations from pipe surfaces indicated that neither chlorine nor chloramine residuals prevented microorganisms from accumulating within the sediments attached to the pipe surface. This result may be of special importance to an understanding of how microbial processes can proceed in water mains, even where low bacterial counts and sufficient disinfectant residuals are observed in samples of the bulk water.
 - f. The addition of the polyphosphate compounds, with and without the addition of the disinfectants chlorine and chloramine, sometimes resulted in increased deposition on pipe surfaces and sometimes in reduced deposition. The results were mixed and inconclusive.
6. The operation of a laboratory-scale pipe loop system simulating a water distribution system showed the following water quality changes:
- a. The oxidation of iron metal in the pipe loops was principally responsible for contributing iron to the water.
 - b. The oxidation of iron results in the depletion of oxygen. In general, the major depletion of oxygen takes place immediately after the oxygenated water comes in contact with iron. Thereafter, the utilization of dissolved oxygen is minimal. In essence, the limited accessibility of oxygen to iron metal as a result of the formation of hydrated ferric oxide films on the metal surface reduces the rate of iron oxidation.

- c. Hydrogen ion concentration, alkalinity, and hardness may change as a result of iron oxidation.
 - d. In general, the variations in concentrations of sulfate and dissolved sulfide in loop water were not appreciable. Thus it was difficult to ascertain their importance as monitoring parameters of water quality changes. This observation does not necessarily imply that these water quality parameters are not important in monitoring water quality deterioration in distribution systems.
 - e. The total organic carbon concentration in water was important in estimating the potential capacity for organism growth in the pipe system. Since the test water contained exceptionally small amounts of total organic carbon, a relatively small amount of microbial activity was observed in the pipe loop systems.
 - f. The bacterial plate counts of water were low when microorganisms were enumerated according to the Standard Methods (95). Higher plate counts were obtained when the enumerations of organisms were performed at lower temperatures and at extended incubation period.
 - g. As with earlier field survey experiments, a wide variety of physiologically different populations of microorganisms was observed in the pipe loop system. For instance, aerobic and facultatively anaerobic heterotrophs, autotrophic nitrifying organisms, denitrifying organisms, nitrogen-fixing organisms, iron-precipitating organisms, sulfate-reducing organisms, sulfur-oxidizing organisms, and stalk-producing organisms were cultured. The cellular morphology of the observed microorganisms varied from cocci, bacilli, and spirillum to pleomorphic forms. Their roles in the microbiotic cycles of elements such as carbon, nitrogen, sulfur, iron, etc. need to be further evaluated.
7. An evaluation of the effect of microbial growth on the corrosion rate of pipe materials, cast iron, and steel, in the pipe loop system was inconclusive. But the evaluation of pipe sediment deposits delineated the formation of corrosion products as cast iron and steel test specimens were oxidized in oxygenated water. The measurement of solids followed

the progress of iron oxidation with time. The rate of iron oxidation was difficult to ascertain, since the test pipe sections that were analyzed were interconnected within a pipe loop system.

Attempts to relate bacterial growth to corrosion rates and increases in volatile solids yielded insufficient data, since only a small quantity of organic carbon could be accounted for from the viable cell counts.

8. From the batch culture corrosion studies of cast iron test specimens exposed to pipe loop water (with and without the supplementary sediments from the pipe loop system), the following conclusions were derived:
 - a. Aquatic microorganisms can maintain viability at the density at which they are normally found in their natural habitat (the water distribution system), if the same population mixture is cultured together.
 - b. The dissolved oxygen was the most important controlling parameter in the oxidation of iron. The relative effect of oxygen on the corrosion rate of cast iron exposed to tap water was much larger than any other influence, including that of microbial activity. More than 2000 mg/dm² corrosion intensity of cast iron was observed in a system with more than 7 mg/l dissolved oxygen, whereas only 200 mg/dm² corrosion intensity of cast iron was observed in a system with less than 2 mg/l dissolved oxygen (26-day exposure).
 - c. In the presence of microorganisms, the corrosion intensity of cast iron test specimens increased by about 500 mg/dm² for specimens exposed to pipe loop water for 26 days. Corrosion intensities of cast iron test specimens exposed to pipe loop water less than 10 days did not show any difference between systems with and without the loop water organisms.
 - d. Evidence of localized corrosion on cast iron test specimens in the presence of microorganisms was clearly seen in this study. A major effect of microorganisms on corrosion of pipe walls in the distribution system might be that of promoting localized corrosion on pipe surfaces with possible formation of "pits" in pipe mains.

- e. Changes in alkalinity were observed in all test menstruum. A decrease in alkalinity was attributable to the formation of ferrous carbonate between oxidized iron and bicarbonate ion in the test menstruum.
9. The results of the studies to determine the effectiveness of polyphosphate compound additions to water supplies for corrosion prevention were as follows:
- a. In batch test systems, the addition of commercial phosphate products such as sodium metaphosphate, sodium hexametaphosphate, and zinc polyphosphate did not effectively decrease the corrosion rate as measured by ASTM test (104) of cast iron test specimens suspended in the galvanic test systems (both in unsaturated and supersaturated states of calcium carbonate) until a sufficient amount of phosphate (greater than 20 mg/l as P_2O_5) had been added. On the other hand, zinc polyphosphate did not decrease the corrosion rate of cast iron test specimens in the non-galvanic test systems until phosphate dosages greater than 10 mg/l had been added.
 - b. The rate of corrosion of cast iron test specimens at a polyphosphate dosage of 20 mg/l as P_2O_5 can be reduced by increasing the total alkalinity, pH, and calcium concentrations as well as by decreasing the concentration of dissolved oxygen.
 - c. In waters supersaturated with calcium carbonate, the calcium hardness is observed to decrease, following approximately zero order kinetics, in the absence of condensed phosphate compounds. But the addition of condensed phosphates at dosages as low as 2 mg/l as P_2O_5 tended to sequester calcium and prevent precipitation of calcium carbonate.
 - d. High alkalinity waters tended to sustain condensed phosphate in the system.
 - e. At a polyphosphate dosage of 20 mg/l as P_2O_5 , the corrosion rates decreased as condensed phosphates accumulated on the cathode with pH in the range of 8.6 to 8.9. There did not appear to be a relationship between anodic corrosion and the total weight of precipitate deposited, however.

- f. At a polyphosphate dosage of 20 mg/l as P_2O_5 , more condensed phosphate accumulated on the cathode as calcium concentrations increased from 70 to 500 mg/l as $CaCO_3$. The anodic corrosion rate decreased with increasing calcium ion.
- g. Condensed phosphate compounds, not orthophosphate, forming deposits on the cathode, not the anode, are most effective in inhibiting corrosion.
- h. In continuous flow corrosion tests, 2.75 mg/l as P_2O_5 of Calgon C-39 sodium-potassium-zinc phosphate, 10 and 20 mg/l as P_2O_5 of Calgon TG-10, sodium-zinc phosphate inhibited corrosion of cast iron test specimens during the first 6 hours of exposure.
- i. In prolonged studies, dosages greater than 20 mg/l as P_2O_5 decreased the cast iron corrosion rate by about 56% for 28 days of exposure in the continuous flow system, whereas a dosage of 10 mg/l as P_2O_5 produced no corrosion inhibition. Low dosages may have, in fact, increased the corrosion rate by as much as 14%.
- j. Conventional corrosion indices, such as Langelier's saturation index (L.I.) and Ryznar's stability index (R.I.), were unable to indicate the $CaCO_3$ deposition or dissolution tendencies of phosphate-enriched waters, since the equilibrium chemistry of the phosphate-enriched water is different from that of the natural bicarbonate-buffered water.
- k. With the addition of 5 mg/l Calgon's C-39 sodium-potassium-zinc phosphate (2.75 mg/l as P_2O_5), standard plate bacterial counts increased up to 30 times as compared with the control during 1.5 hours of detention in the continuous-flow water systems. From the addition of 18 and 36 mg/l Calgon TG-10 sodium-zinc phosphate (10 and 20 mg/l as P_2O_5 , respectively), standard plate counts increased up to 80 times as much as the control. In both cases, a slight dissolved oxygen reduction occurred in the phosphate-enriched systems. In practice, chlorine residuals may be needed to control additional microbiological growth caused by phosphate additions to water distribution systems.

1. Increasing polyphosphate dosages from 2 to 40 mg/l as P_2O_5 tended to increase both total particle numbers and turbidities within 10 minutes of reaction time. Moreover, higher polyphosphate dosages of 20 and 40 mg/l as P_2O_5 tended to result in the formation of larger particles.
- m. Increasing calcium ion concentrations from 20 to 500 mg/l as $CaCO_3$ equivalent (0.4 to 10 meq/l) tended to increase total particle numbers and size.

Section 3

RECOMMENDATIONS

The survey of water utilities conducted as part of this study indicates that a majority of U.S. water utilities encounter water quality problems which originate in the distribution system. On occasion, the problems described may be encountered by virtually all water utilities, particularly following main breaks, main flushing programs, fires or other events which lead to high velocities in water mains. High velocities lead to the sloughing of materials which have accumulated over a period of time owing to either chemical instability (tendency to form inorganic deposits) of the water or its tendency to promote the growth of microorganisms. The formation of inorganic or biological deposits in water mains is often countered by the application of chemicals, such as chlorine, polyphosphates or silicates, to mitigate the effects of excessive accumulations. These alterations in finished water quality, in turn, may diminish or increase corrosion rates in water main and household supply lines.

The following general recommendations are therefore directed to water utility managers seeking to evaluate the stability of treated water in a water distribution system. They prescribe:

- a distribution system sampling program
- analyses of distribution system water samples
- measurement of the rates of accumulation of deposits and the corrosion of metals
- evaluation of remedial measures
- tests of long-term stability of treated water

Most of the methods recommended are detailed in the text of this report.

SAMPLING PROGRAM

Municipalities that are aware of water quality problems in their distribution systems should initiate a long-term, continuous, water sampling and analysis program. Numerous samples from taps and hydrants should be collected throughout the system, particularly in areas where water quality problems

are reported and during periods of warm weather (higher water temperatures). Tap water quality can be directly compared with treated water being introduced to the system. However, hydrant samples will often include deposits removed from the surface of water mains. These solids should be separated and analyzed separately because they provide a special opportunity to observe the material which may be directly responsible for complaints or for altering water quality. A specific sampling protocol must be designed for the system under study based on system size, defined problem areas and the analytical capability routinely available. Adequate analytical facilities will be required because the analytic program must be fairly comprehensive to be effective.

ANALYSES

Since chemical and microbial analyses are costly, the analytic program should be carefully prescribed to address specific concerns. A comprehensive analytic program would include the following:

Chemical Analyses

Conventional inorganic analysis: Ca^{++} , Mg^{++} , H^+ , HCO_3^-

Analysis for evidence of microbial activity:

Loss of chlorine residual: HOCl , chloramine

Depletion of dissolved oxygen: $\text{O}_2(\text{aq})$

Nitrification, denitrification: NH_4^+ , NO_2^- , NO_3^-

Acid production: decrease in alkalinity

Sulfate reduction: SO_4^{--} , H_2S , metal sulfides

Analysis for microbial substrates:

Carbon source: dissolved organic carbon, CH_4

Nitrogen source: NH_4^+

Phosphorus source: total phosphate

Analysis for reactions between chlorine and microbial extracellular excretions: trihalomethanes

Microbial Analyses

Total enumeration of microorganisms: Direct count, e.g., acridine orange direct count (AODC)*, standard plate count.

*Newly developed rapid techniques for the direct total count of microorganisms employ fluorochromes, membrane filtration and epifluorescent microscopy. These techniques are far superior to plate count techniques for estimating the total population of organisms in distribution system water samples.

Enumeration of specific organism groups: sulfur-oxidizing, nitrogen-fixing, nitrifying, denitrifying, sulfate-reducing, iron-precipitating organisms.

Sediment Analyses

General composition of sediments: total and volatile solids, calcium, magnesium, iron, sulfides, silicates, phosphates.

Enumeration of Specific Organism Groups: as above

Particular attention should be given to the microbial and sediment analyses since it is in those areas that most water utilities lack data and insight.

ACCUMULATION OF DEPOSITS AND CORROSION

A pipe manifold system has been developed and tested as part of this study. It provides a simple means for observing the accumulation of deposits and the corrosion of test specimens in continuous flow systems. Such manifold systems, installed at various distribution system locations, can provide, first, a visual, then, a quantitative indication of sediment accumulation, biological growth and corrosion. Removable pipe sections in the manifold permit estimates to be made of the rates of corrosion and deposition.

REMEDIAL MEASURES

The pipe manifold apparatus also promises to serve as a useful tool for evaluating the effectiveness of changes in water treatment aimed at curbing distribution system problems. Rates of solids deposition, biological growth and corrosion must be determined at various locations both before and after major treatment modifications. The continuing cost of the use of supplementary chemicals, plus the mixed results which have been qualitatively observed in various water systems make a formal assessment of effectiveness highly desirable. The results of corrosion studies using polyphosphate formulations in the present study have indicated that, under some circumstances, these chemicals may increase corrosion rates and promote bacterial growth.

STABILITY OF TREATED WATER

Commonly, assessments are made of the chemical "stability" of water, i.e., equilibrium with respect to calcium carbonate. However, the biological "stability" of treated drinking water has never been defined or evaluated owing to the assumption that with chlorination, microbial growth was not possible.

However, since the sediments from the distribution systems may supply nutrients and consume reactive chlorine residuals, microorganisms may thrive. The presence of significant amounts of dissolved carbon, nitrogen and phosphorus in treated water may stimulate excessive microbial accumulations in water mains which may subsequently slough or mediate measurable chemical changes.

A simple batch evaluation of treated water, seeded with microorganisms from sediments from the distribution system, may serve as an indicator of the water's tendency to support diverse organism growth. In turn, such a biological evaluation might serve as a guideline for appropriate treatment to minimize organisms growth.

Biological processes in water distribution systems are poorly understood and rarely evaluated. However, their influence on water quality, sediment accumulation and corrosion may be important. These influences may be evaluated using some of the methods developed and tested as part of the current study.

SECTION 4

SURVEY OF DISTRIBUTION SYSTEM WATER QUALITY PROBLEMS

SURVEY QUESTIONNAIRE

To determine the extent and nature of water quality problems in distribution systems in the United States, a questionnaire was developed for water utility managers. This comprehensive questionnaire includes questions relating to raw and finished water quality in the distribution system, type of treatment, chemicals used for treatment, type and age of pipe used in the distribution system, frequency and nature of consumer complaints, and remedial measures currently used. A copy of the questionnaire is included in Appendix B. With the support of the AWWA Research Foundation, this questionnaire was mailed to some 2400 water utilities throughout the United States. A total of 354 questionnaires were returned. The utilities responding encompass a broad spectrum of population size (Table 1). The sources of the water supplies have been categorized by EPA regions (Table 2).

The survey results indicate that 44.6% of responding utilities obtain water supply from ground water sources, 20.6% from lake water sources, and 14.4% from river sources. In addition, many utilities report using multiple water sources. About 20% of the utilities surveyed use at least two or more water supply sources. The type and numbers of water quality problems which have been reported by the utilities are listed in Table 3. The data indicate that taste and odor problems are the most frequently reported consumer complaints. Over 60% of the responding utilities reported these problems. "Red" water ranked second with 47.7% of the utilities reporting this problem. 46% reported problems with cloudiness of water. "Black" water was reported by 16.7% of the utilities. At least 80% of the utilities reported experiencing two or more types of water quality problems as reflected by their consumer complaints. The preliminary results indicated that, irregardless of the water supply sources, sizes of the utilities or the geographical regions, virtually every responding utility experiences some water quality problem in the distribution system. This survey also indicated that, presently, the most frequently practiced remedial treatment method is a main flushing

Table 1

Classification of the Responding Utilities With Respect to Population Served

Population Served	Number of Utilities	Percentage
Less than 1000	28	8%
1000 - 5000	85	24%
5000 - 10,000	39	11%
10,000 - 50,000	104	29%
50,000 - 100,000	35	10%
Greater than 100,000	54	15%
Not Listed	9	3%

Table 2

Sources of Water Supply for Utilities Surveyed

EPA Region	Number of Responding Utilities	Ground Water	Lake Water	River Water	Ground and River	Ground and Lake	River and Lake	Ground River, & Lake	Not Listed
I	12	4	6	0	0	2	0	0	
II	25	11	7	3	3	1	0	0	
III	24	3	7	9	1	0	3	1	
IV	44	25	7	6	2	2	1	1	
V	97	57	25	5	5	3	1	0	1
VI	21	5	10	2	1	3	0	0	
VII	39	18	2	8	7	3	0	0	1
VIII	18	5	2	4	2	1	3	1	
IX	47	21	7	6	8	1	2	1	1
X	27	9	0	8	7	0	3	0	
Total	354	158	73	51	36	16	13	4	3
Percent		44.6%	20.6%	14.4%	10.2%	4.5%	3.7%	1.1%	0.8%

Table 3

Water Quality Problems Cited by Utilities Surveyed

EPA Region	Taste	Odor	Cloudi-ness	"Red" Water	"Black" Water	Others*
I	6	6	5	6	1	2
II	10	9	5	12	5	3
III	16	16	14	10	6	2
IV	35	28	22	24	9	7
V	59	60	39	62	19	9
VI	14	15	12	7	1	3
VII	27	20	21	17	10	4
VIII	11	9	10	5	2	3
IX	32	30	23	16	5	13
X	20	16	14	10	1	6
Total	230	209	105	169	59	52
Percent	65.0%	59.0%	46.6%	47.7%	16.7%	14.7%

* Others: Pressure, Chlorine, Sand, Color

program. Other remedial measures include increases in chlorine residuals at the plant, rechlorination in the distribution system, adjustment of pH for calcium carbonate deposition and the addition of sequestering agents such as polyphosphates.

SURVEY OF WATER QUALITY IN MISSOURI WATER DISTRIBUTION SYSTEMS

A number of water distribution systems in Missouri were examined to survey chemical and the microbiological changes in their distribution systems. The main objective of this investigation was to determine whether the observed quality changes in distribution systems are biologically mediated.

Water quality changes and microbial growths in water pipes have been reported by other investigators. However, the nature and roles of microorganisms in influencing water quality changes in distribution systems have not been evaluated systematically.

Initially, methods for sampling and analyzing water from a distribution system were field-tested in several Missouri cities. The cities included Moberly, Macon, Chillicothe, Kansas City, Marshall and Columbia, Missouri. The utility managers in these cities indicated that they had experienced problems with water quality changes in their distribution systems.

An important objective of the sampling program was to develop a method for obtaining representative samples from a distribution system. Sampling locations should be at points which are representative of the conditions within the distribution system. Water samples were collected both at the taps of various distribution system locations and at nearby hydrants.

Hydrant Sampling

Fire hydrant discharges can provide water samples containing accumulated growths and sediments from the distribution pipe walls. Analysis of the materials dislodged from the pipe walls would provide insight into the ecosystem that exist within the distribution system. Hydrant water samples, however, must not be collected from the hydrant connecting pipes because water quality may not be representative of distribution main water quality.

Some fire hydrants have a drain valve at the bottom of the stem to drain water from the riser pipe. Draining of the stem water prevents freeze damage of the hydrant. The drain valve is closed when the fire hydrant is fully open, but it is opened when the hydrant valve is closed. During hydrant water sam-

pling, the possibility exists that water from the hydrant base may be sucked up through the drain valve if the hydrant is only partially opened. Improper water sampling may also result from collecting water from the riser pipe and the pipe connecting to the distribution mains.

It is difficult to enumerate all microorganisms that might be present in a water sample because no single medium, temperature or choice of incubation time can insure recovery of all organisms present in water. However, specific members of the bacterial population in water can be enumerated and their numbers related to the microbiological quality of a distribution system.

In an effort to develop a better cultivation method for enumerating microbial populations in distribution main samples, both incubation temperature and time were varied from the standard plate count protocol. Several media were investigated to determine their ability to support the microbial population from distribution system waters.

A longitudinal study of five water distribution systems in Missouri was conducted to evaluate the (sampling techniques and) water quality changes in distribution systems and to attempt to relate observed changes to resultant consumer complaints. The five water distribution systems sampled included the Public Water Supply District No. 4 (PWSN No. 4) in Boone County, and Moberly, Boonville, Marshall and Columbia, Missouri.

The Public Water Supply District No. 4 was reported to have problems with "black" water and hydrogen sulfide odor in certain locations of the distribution system. Moberly had been concerned with a "red" water problem in its water system, particularly during the summer and lake turnover periods. Marshall has been plagued with a "red" water problem in its distribution mains. In addition, both the cities of Boonville and Columbia experienced taste and odor problems and some "red" water problems.

A water distribution system is a complicated dynamic system. Therefore, a comprehensive sampling program must be conducted at numerous locations over a prolonged period of time. In the present study, only a single sampling was possible. Information concerning the distribution system was obtained from the water utility managers. The history and present status of each distribution system was examined and a coordinated sampling program was devised for each system.

Public Water Supply District No. 4, Boone County, Missouri,
Water System (PWDS No. 4)

The public water supply district No. 4 is a rural water district which supplies water in the areas Northeast of Columbia, Missouri. Three 340 meters deep wells supply the water for the district. The intake pipes for these wells are located at a depth of 180 meters. Although the district has all three wells in operation, its need was mainly supplied by Wells No. 1 and No. 2.

Well No. 3 has a hydropneumatic tank connected to the discharge pipe which allows intermittent well pump operation. Therefore, Well No. 3 supplies water only if the pressure is low. Several residents close to Well No. 3 experienced severe black water problems after Well No. 3 began its operation. Analysis of samples from the different wells indicated that Well No. 3 had a higher iron concentration than Wells No. 1 and 2.

The water is pumped to consumers without any treatment except for occasional chlorination. Almost the entire water distribution system consists of 5 cm and 10 cm diameter polyvinyl-chloride (PVC) pipes. However, there were several sections of cast iron pipes in the distribution system. Moreover, the service connection pipe for the house with the severe black water problems was made of galvanized iron.

Moberly, Missouri Water Distribution System

The city of Moberly obtains its water from a surface water impoundment. A 90 cm diameter transmission pipe conveys the impounded water to the filtration plant. The water treatment processes employed are coagulation, sedimentation, filtration and chlorination. The water treatment plant is located at the northwest corner of the city. Two 35 cm diameter mains and one 30 cm diameter main carry the treated water from the treatment plant to the city's two storage tanks.

"Red" Water problems were experienced by a number of consumers who reside at the farthest part for the treatment plant. However, residents in other part of the city also experienced discolored water from their taps. Problems of discolored water were most severe during the summer and lake turnover periods. A somewhat different type of discolored water problem was observed in southwest portions of the city. Residences that were on dead-end mains occasionally experienced severe black water problems.

Marshall, Missouri Water Distribution System

Marshall, Missouri obtains its water from wells. The groundwater is treated by aeration, lime softening, filtration and chlorination. The distribution mains are 60 percent cement-lined and 40 percent asphalt-lined cast iron pipes. Consumer complaints of red water and turbidity were generally received from one section of the city.

Preliminary microbiological analysis showed the presence of a variety of microorganisms including filamentous iron bacteria, sulfate-reducing organisms and actinomycetes. The water utility maintains its water distribution system by main flushing and high chlorine residuals.

Boonville, Missouri Water Distribution System

The Boonville, Missouri water supply is derived from the Missouri River. Water treatment consists of presedimentation, coagulation, filtration and disinfection by chlorine. For coagulation, both alum and lime are used. Polymer is used as a coagulant aid. Polyphosphate is added to stabilize the finished water. About 2 mg/l ammonia-nitrogen is added to the finished water to form a combined chlorine residual. Most of the distribution mains are laid with unlined cast iron pipes.

Columbia, Missouri Water Systems

Columbia, Missouri obtains its water from wells in the Missouri River flood plain near McBaine, Missouri, which is about nine miles south of Columbia. The well aquifers are hydraulically connected to the Missouri River so that the water quality is similar to that of the river. The water treatment process consists of lime softening, filtration and disinfection. Polyphosphate is added before the filter to procure longer operation of the filter. There are a few wells in the city of Columbia that augment the supply to the system in times of emergency or low pressure. These well supplies are not treated except for occasional chlorination.

In Columbia, the treated water is first transported to one large underground storage tank located at the western part of the city. After booster chlorination, the water is pumped to the distribution system, including the city's three storage tanks.

Most of the water mains in the Columbia Water system are lined with either cement or bituminous material. Although deposits of calcite and iron oxide precipitates were observed, significant corrosion of the underlying cast iron pipe was not indicated.

Occasional consumer complaints have been related to red water and taste and odor problems. High bacterial counts were noted in some portions of the distribution system.

MATERIALS AND METHODS

Evaluation of Sampling Techniques

Sampling at Consumer's Tap--Before collecting water samples, tap aerators were removed. Cotton swabs with 70 percent ethyl alcohol were used to disinfect the openings of water faucets. Necessary precautions, as described in Standard Methods, 14th ed. (95) for bacteriological water sampling were observed when tap water samples were collected. In particular, sufficient flushing time was allowed to collect only the samples from the distribution main rather than the service line.

Sampling at Fire Hydrants--Experiments were conducted to determine the consistency and validity of hydrant water sampling. The experiment involved collection and analyses of water samples from fire hydrants as a function of elapsed time after full opening of the hydrant. A number of sets of water samples were collected on two separate dates (September 30, 1976 and October 13, 1976) from the Columbia, Missouri water distribution system. The locations of hydrants examined are shown in Figure 1. The description of the test hydrants were shown in Table 4. The following chemical and microbiological analyses were performed on these water samples: pH, alkalinity, hardness, free and total chlorine residuals, total iron and ammonia-N.

The methodology for these analyses were as described in Standard Methods (95). DPD-FAS titration methods were used to measure free and total chlorine residuals. The phenanthroline colorimetric method was used to measure total iron concentrations. EDTA and dilute sulfuric acid titration methods were used to measure total hardness and alkalinity, respectively. Microbiological analysis was limited to the enumeration of organism growth on standard plate count agar at room temperature after five days.

Evaluation of Microbial Plate Count Method

Pour plates using standard plate count agar were incubated at 35°C and 20°-22°C for 2, 5, 7 and/or 10 days. The bacterial density of the water was calculated by enumerating the viable colonies on plates after each incubation period.

Other growth media, including the standard plate count medium diluted one-half, one-fifth, one-tenth and one-fiftieth of the original concentration, were evaluated for their effi-

Table 4. Description of Hydrants Examined

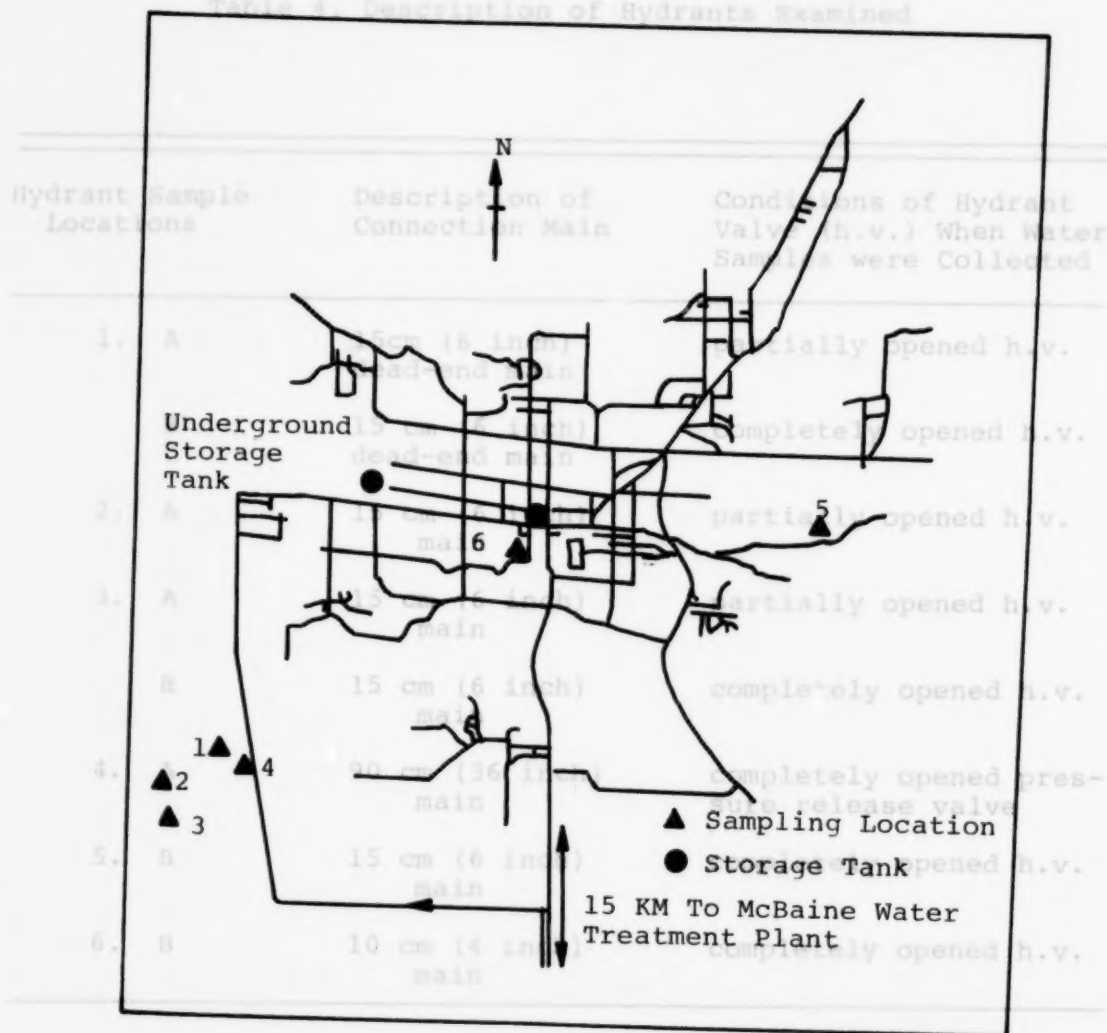


Fig. 1 Locations of Fire Hydrants Examined to Evaluate Sampling Techniques - Columbia, Missouri Water Distribution System

B. Experimental Date: October 13, 1976

Table 4. Description of Hydrants Examined

Hydrant Sample Locations	Description of Connection Main	Conditions of Hydrant Valve (h.v.) When Water Samples were Collected
1. A	15cm (6 inch) dead-end main	partially opened h.v.
B	15 cm (6 inch) dead-end main	completely opened h.v.
2. A	15 cm (6 inch) main	partially opened h.v.
3. A	15 cm (6 inch) main	partially opened h.v.
B	15 cm (6 inch) main	completely opened h.v.
4. A	90 cm (36 inch) main	completely opened pressure release valve
5. B	15 cm (6 inch) main	completely opened h.v.
6. B	10 cm (4 inch) main	completely opened h.v.

A. Experimental Date: September 30, 1976

B. Experimental Date: October 13, 1976

ciency in supporting microbial growths. In addition, the basal mineral medium with glucose and another mineral medium with a number of organic constituents (R2A)* were examined. The results of bacterial density were compared to the value obtained by standard plate count.

Evaluation of Water Quality in Missouri Water Distribution Systems

Examination of water quality changes in distribution systems began with the selection of representative sampling locations. Usually water samples were collected from a number of distribution mains including those in areas with reported water quality problems.

For the initial evaluation of the distribution systems, field testing equipment was employed to measure pH, total chlorine residuals, dissolved oxygen, total iron and hydrogen sulfide. Although the field testing equipment was less accurate than laboratory methods, it enabled the investigators to observe the results of the chemical tests at the site of sample collection. Based on this initial evaluation, a more comprehensive evaluation was planned.

Sampling Methods--For the five water distribution systems examined, the following sampling methods and water quality analyses were utilized. Sample bottles were sterilized in the autoclave, and one ml of sterile 0.25N sodium thiosulfate was added to each bottle to dechlorinate chlorine residuals. Water samples were collected at the tap of consumer's residences and of fire hydrants. Hydrant sampling was conducted with the valve completely opened. Aseptic procedures were followed as specified in Standard Methods (95).

Samples were brought to the University of Missouri-Columbia laboratory for microbiological and chemical analyses which included pH, free and combined chlorine residuals, dissolved oxygen, dissolved sulfide, sulfate ion, total iron, alkalinity, hardness, ammonium ion, nitrate, total phosphate and total organic carbon.

* Composition of R2A Medium: Yeast extract, 0.5 g; proteose peptone No. 3, 0.5 g; casamino acids, 0.5 g; glucose, 0.5 g; soluble starch, 0.5 g; K_2HPO_4 , 0.4 g; $MgSO_4 \cdot 7H_2O$, 0.05 g; sodium pyruvate, 0.5 g; agar, 15 g; distilled water, 1000 ml; adjust pH to 7.2

Chemical Analysis--The methods of analyses were as specified in Standard Methods (95). Available chlorine residuals in water were measured by the DPD-FAS titration method. The titration method was preferred because the presence of sediment in hydrant flushing samples interfered with the DPD colorimetric method. Dissolved sulfide was measured by the iodine - thiosulfate titration method. Sulfate analysis was performed by the turbidimetric method. The nitrate analysis was by the brucine sulfate colorimetric method. The total organic carbon concentration was measured using the Beckman Total Organic Carbon Analyzer. The Ascorbic Acid Reduction Method was employed to measure the total phosphate concentrations. In general, water samples were analyzed as soon as they were brought to the laboratory. Occasionally, water samples were refrigerated at 5°C if analysis could not be conducted immediately.

Microbiological Analysis--The microbiological analyses of water samples were conducted mainly to identify the predominant microorganisms in distribution systems. Dechlorinated water samples were inoculated into various selective enrichment culture media as presented in the following list.

1. Nutrient broth (BBL)
2. Thioglycollate medium, Brewer modified (BBL)
3. Nitrogen-fixing basal medium
4. Reinforced Baar's liquid medium
5. Thiosulfate mineral medium
6. Winogradsky's iron enrichment medium
7. Winogradsky's modified medium for nitrifying bacteria
8. Stalk and bud-producing bacteria enrichment medium
9. Czapek's broth medium
10. Yeast extract-glucose medium

Briefly, they were prepared in the following fashion:

Nitrogen-fixing basal medium - pH 6.9 ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 0.02%; CaCO_3 , 0.05%; $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, 0.025%; $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$, 0.05%; $\text{K}_2\text{HPO}_4 / \text{KH}_2\text{PO}_4$, 0.1%; glucose, 0.5%; mannitol, 0.5%)

Reinforced Baar's Medium - pH 7.0, (Na_2HPO_4 , 0.05%; NH_4Cl , 0.1%; CaSO_4 , 0.1%; $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 0.2%; $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$, 0.05%; sodium thioglycollate, 0.6%; ascorbic acid, 0.01%; sodium lactate, 0.35% and yeast extract, 0.1%) (freshly prepared on the day of experiment).

Thiosulfate mineral medium - pH 6.9, (Sodium thiosulfate, 0.5%, NH_4Cl , 0.1%; $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, 0.05%; K_2HPO_4 , 0.1%; yeast extract, 0.005%)

Winogradsky's Iron enrichment medium - pH 6.8 (NH_4NO_3 , 0.05%; $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 0.05%; K_2HPO_4 , 0.05%; $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, 0.02% and ferric ammonium citrate, 0.5%)

Winogradsky's modified medium for nitrifying bacteria - pH 8.0, ($(\text{NH}_4)_2\text{SO}_4$, 0.2%; K_2HPO_4 , 0.1%; $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 0.05%; NaCl , 0.05%)

Stalked and budding bacteria enrichment culture medium - pH 7.2, ($(\text{NH}_4)_2\text{SO}_4$, 0.05%; $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, 0.001%; KH_2PO_4 , 0.1%; Na_2HPO_4 , 0.2%; $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 0.005%; $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$, 0.002%)

Czapek's broth medium - pH 7.0, (glucose, 1.5%; glycerol, 1.5%; K_2HPO_4 , 0.001%; $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 0.05%; KCl , 0.05%; $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 0.001%)

Yeast extract - glucose medium - (glucose, 1%; peptone, 0.3%; yeast extract, 0.5%) Adjust pH to 7.8 after sterilization.

All the media were sterilized at 121°C for 20 minutes. The sterilized enrichment culture media were then distributed into sterile tubes.

For anaerobic and microaerophilic organisms, screw-capped tubes with inoculum were completely filled with thioglycollate medium.

Cultivation was at room temperature (20°C - 25°C). Incubation time was extended to two to three weeks in order to provide longer incubation times for slow-growing organisms.

Verification of organism growth in various enrichment culture tubes was conducted by means of direct microscopic examination for cellular morphology. Since microscopic examinations cannot differentiate viable cells from dead cells, positive cultures were subcultured into appropriate solid media to isolate organisms in pure culture forms for further identification. Gram staining, oxidase reaction, and the API system of identification were employed to identify purified isolates. Photomicrographs of the isolates were made to aid in identification.

RESULTS AND DISCUSSION

Evaluation of Hydrant Sampling Methods

The results of chemical and microbiological analyses of water samples from hydrant flushings from the Columbia, Missouri water distribution system are presented in Tables 5 and 6. The studies were conducted to evaluate hydrant sampling and techniques as a function of flushing time. The microbiological analysis was the enumeration of microorganisms in standard plate count medium.

Table 5 Chemical and Microbiological Analyses of Water Samples from Hydrant Flushings
(Columbia, Missouri, September 20, 1976)

Hydrant Sample Locations	Flushing Time sec.	Chlorine Residuals		Total Iron mg/l	pH	Alkalinity meq/l	Hardness mg/l as CaCO ₃ eq.	NH ₃ -N mg/l	Bacterial Plate Count No./ml
		Free Cl ₂ mg/l	Total Cl ₂ mg/l						
1A	0	0.0	0.1	1.0	8.4	3.8	196	0.1	1.0x10 ⁴
	10	0.1	0.3	1.0	9.1	3.1	168	-	5.0x10 ³
	20	0.1	0.3	0.7	9.0	2.9	184	0.3	2.0x10 ³
	30	0.2	0.4	0.8	9.2	4.6*	156	-	1.0x10 ³
	60	0.4	0.4	0.4	9.1	3.1	160	-	1.4x10 ²
2	0	0.1	0.4	1.0	9.2	2.7	152	-	2.0x10 ³
	10	0.4	0.6	1.0	9.3	-	-	0.2	1.1x10 ³
	20	0.4	0.6	1.0	9.2	5.2*	152	0.2	8.7x10 ²
	30	0.5	0.7	1.0	9.3	5.0*	-	0.2	4.0x10 ²
	60	0.5	0.6	1.0	9.2	5.2*	152	0.2	8.0x10 ¹
3	0	0.2	0.5	1.0	9.1	2.6	152	0.2	2.3x10 ²
	10	0.6	0.8	0.2	9.1	2.6	148	-	4.9x10 ¹
	20	0.2	1.0	0.2	9.0	-	-	-	9.8x10 ¹
	30	0.2	1.0	0.3	9.3	-	-	0.6	7.9x10 ¹
	40	0.6	1.0	0.6	-	-	-	0.2	5.1x10 ¹
4	0	0.2	0.6	0.9	8.6	2.9	148	0.2	1.0x10 ³
	15	0.5	0.8	0.3	-	-	-	-	9.5x10 ⁰
	30	0.2	0.7	0.3	8.8	-	-	0.2	1.8x10 ¹
	45	0.6	0.8	0.2	8.6	-	-	0.2	1.0x10 ¹

* Visible CaCO₃ precipitate

Table 6 Chemical and Microbiological Analyses of Water

Samples from Hydrant Flushings (Columbia, Missouri, October 13, 1976).

Sample Location	Flushing Time sec.	Chlorine Residuals		Total Iron mg/l	Bacterial Plate Count No./ml
		Free Cl ₂ mg/l	Total Cl ₂ mg/l		
1B	0	0.2	1.9	0.6	1.5 x 10 ¹
	15	0.3	2.0	0.9	1.0 x 10 ¹
	35	0.4	2.1	1.0	1.0 x 10 ¹
	60	0.5	2.3	1.0	1.0 x 10 ¹
	120	-	-	0.1	1.0 x 10 ¹
3B	0	0.5	1.6	0.2	1.0 x 10 ¹
	15	0.4	1.3	0.1	1.0 x 10 ¹
5	0	0.1	0.2	1.0	7.5 x 10 ³
	15	0.2	0.4	0.2	7.6 x 10 ²
	30	0.4	0.5	0.2	8.1 x 10 ¹
	60	0.4	0.5	0.2	2.5 x 10 ²
	90	0.4	0.5	0.2	1.5 x 10 ²
6	0	0.1	0.1	1.0	1.0 x 10 ³
	15	0.1	0.1	1.0	3.5 x 10 ²
	30	0.1	0.6	1.0	5.3 x 10 ¹
	60	0.6	1.0	0.5	1.0 x 10 ¹
	90	0.3	1.0	0.5	1.0 x 10 ¹

(1) Sample location No. 1: Initially, the hydrant flushings were rusty red. After 15 seconds of full flow, the red water started to clear. However, the water did not clear completely during 60 seconds of flushing. Instead, after the initial red water, a grayish colored water was discharged. The pH of the early flushing samples was lower than that of the latter flushing samples. Total chlorine residuals increased with flushing time, while the total iron concentration decreased with flushing time. Both alkalinity and hardness decreased somewhat with time. The 30 second water sample exhibited a precipitate of calcium carbonate and showed a high alkalinity. As expected, the initial water sample was not representative of the water in the distribution main since it had a high iron concentration (~1mg/l) and only a negligible chlorine residual.

Chlorine residuals observed in water samples from sample location No. 1 were generally low (0.05 to 0.45 mg/l total chlorine). This hydrant had not been flushed for several months prior to this experiment. Microbiological analyses showed high plate counts (10^3 - 10^4 /ml). Both iron-precipitating bacteria and fungi (yeasts and molds) were observed. A protozoa was detected in the initial water sample.

The same hydrant was sampled on a later date (October 13, 1976). The hydrant had previously been flushed by the City Fire Department at the time location No. 5 was sampled. The initial discolored water did not clear completely until after 100 seconds. The water quality was improved significantly compared to the previous set of samples. In particular, the total available chlorine residuals were high and standard bacterial plate counts were very low. High iron concentrations were observed in samples that were collected after 35 seconds and 60 seconds. The high turbulence created by fully opening the hydrant caused sediments to be suspended and discharged with the water.

(2) Sample Location No. 2: The initial water sample was red colored. Within 10 seconds, the red water cleared. In this case, the water was collected from a discharge stream of low velocity. Water samples were light orange to white in color due to a mixed suspension of calcium carbonate and iron hydroxide precipitates in the flushing samples. The high turbidity was reflected in the total iron analysis. Even the sample obtained after 60 seconds of flushing showed the total iron greater than 1 mg/l. Total chlorine residuals increased with flushing time principally because the free chlorine residuals increased. Microbiological analysis showed a gradual decrease in organism concentration with time of flushing. At least a 60 second flushing time was required before the organism concentration became comparable to that found in the bulk distribution system water.

(3) Sample Location No. 3: The initial water sample was rusty red, but quickly cleared to colorless. However, the water appeared red at times upon continued flushing. The reappearance of the red water was attributed to the high velocity of water which may have created sufficient turbulence to dislodge sediments from the distribution pipe walls. At least 70 seconds of flushing time was required before the water became completely clear. When another set of water samples was collected from location No. 3, the initial discolored water cleared within three seconds. Therefore, water quality was comparable to that found in samples from the main.

Microbiological analyses yielded lower organism concentrations in water samples from Sample location No. 3. With a high velocity flushing program, 10 seconds appeared adequate to obtain water quality comparable to that found in distribution system water.

(4) Sample location No. 4: The analytical results indicate that water quality from the 91 cm water main was comparable to the results obtained from the previous small main hydrant flushing samples, except for lower pH values. Total iron concentrations were lower as flushing progressed, while a slight increase in chlorine residuals was observed.

Microbiological analyses for the Sample location No. 4 was distinct in the organism density decreased two orders to magnitude within 15 seconds of the start of flushing.

(5) Sample location No. 5: Except for the initial sample, the water samples obtained indicated similar chemical and microbiological quality after 15 seconds. Therefore, at this particular hydrant, 15 seconds may have been sufficient to draw water samples from the main pipe.

(6) Sample location No. 6: Iron concentrations were found to be high even in samples collected after 30 seconds of flushing. Organism concentrations decreased nearly two orders of magnitude after 50 seconds of flushing. Generally, the total iron and high turbidities concentrations decreased with time.

The results of analyses for total chlorine residuals and the standard bacterial plate counts in the eight flushing tests are shown in Figures 2 and 3, respectively. The highest chlorine residuals were observed in samples from sample location No. 1B, while the lowest chlorine residuals were observed in large main hydrant. However, the 1B samples were collected just after the City Fire Department had flushed the hydrant. It was evident from this observation that the hydrant condition at the time of sampling was an important factor in determining the samples to be represented as distribution water.

- 1A: 6in dead-end main(P/O) ▼ 3B: 6in main(C/O)
 × 1B: 6in dead-end main(C/O) ▽ 4: 36in main(C/O)
 △ 2: 6in main(P/O) ● 5: 6in dead-end main(C/O)
 □ 3A: 6in main(P/O) ▲ 6: 4in main(C/O)
- (P/O): Partially opened hydrant valve
 (C/O): Completely opened hydrant valve

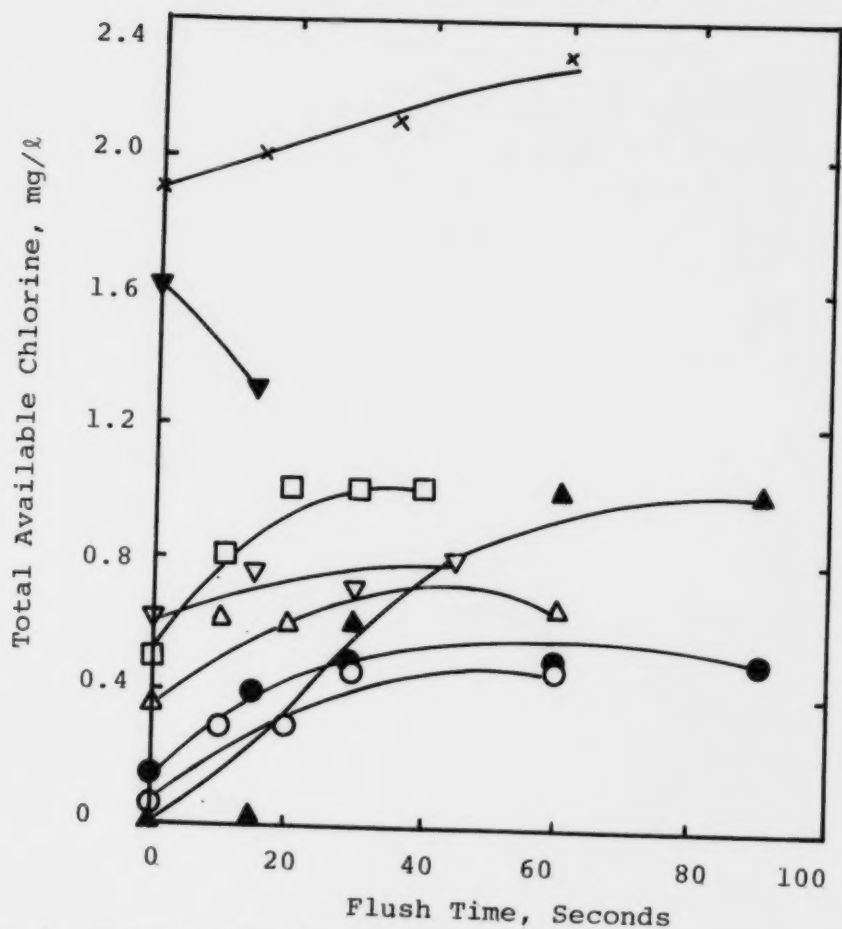


Fig. 2 Chlorine Residuals in Columbia, Missouri Hydrant Water Samples vs. Flush Time

- 1A: 6in Dead-end Main(P/O)
- × 1B: 6in Dead-end Main(C/O)
- △ 2: 6in Main(P/O)
- 3A: 6in Main(P/O)

- ▼ 3B: 6in Main(C/O)
- ▽ 4: 36in Main(C/O)
- 5: 6in Dead-end Main(C/O)
- ▲ 6: 4in Main(C/O)

(P/O): Partially Opened Hydrant Valve
(C/O): Completely Opened Hydrant Valve

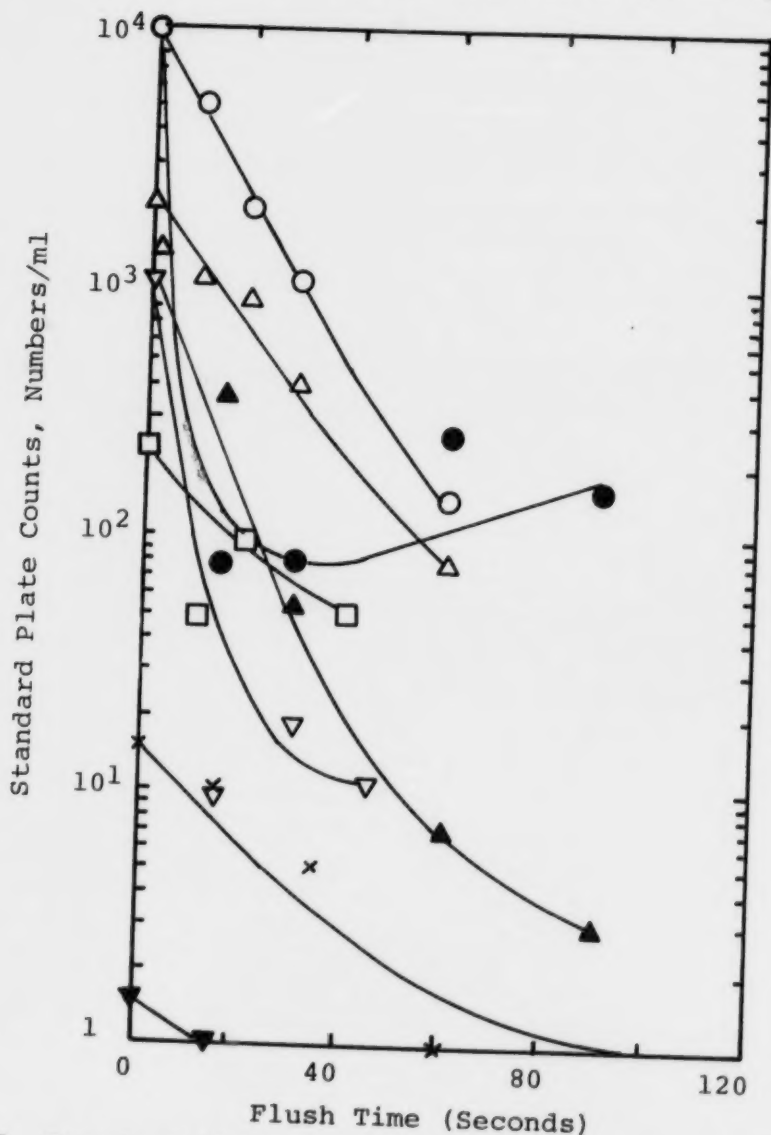


Fig. 3 Standard Plate Counts in Columbia, Missouri Hydrant Water Samples vs. Flush Time

The results of microbiological analyses (Figure 3) showed significant difference among the eight sets. At slow-flushing velocities (Sampling locations No. 1A and 3A), a longer flushing time was required before the water quality was comparable to that of distribution system water. With the high velocity flushing program (Sampling locations No. 1B and 3B), a shorter time was sufficient to obtain representative water samples from a distribution main.

Results of Flushing Studies

The results of the flushing sampling studies indicated that at least 60 seconds should elapse with the hydrant valve fully opened before water samples may be representative of the water in the main. Shorter flushing times may be acceptable if the time of previous flushing is within a few days of sampling time. The quality of water obtained depends on the frequency of routine flushing. Therefore, data should be available as to the time of previous flushing. It was felt that in order to obtain representative water samples from a distribution system, both major and minor mains should be included. The requirements for proper flushing time depends mainly on the flushing velocity and the location of the hydrant. The purpose of hydrant sampling is to obtain samples of distribution system water plus solid materials that can provide information concerning the ecosystem of microbial growths within the distribution system.

It appears that water quality changes in distribution systems should be observed by monitoring both water from the taps of consumer's residences and hydrant flushings.

Evaluation of Microbial Plate Count Method

The results of the microbial plate counts of randomly selected water distribution samples inoculated on the standard plate count medium after 2, 5, 7 or 10 days of incubation are shown in Table 7. Usually, plate counts increased with increasing incubation time. The relative increases in bacterial densities varied with different water samples. It was evident from the data that distribution system organisms grow slowly so that the extension of the conventional incubation period to 5 to 7 days would result in higher microbial plate counts.

When the incubation temperature was lowered to 20°C - 25°C, microbial densities increased 6-80% after 5 days (Samples No. 8-10). It appears that the lower temperature is more favorable for the development of water microorganisms whose natural habitat is in the range of 15°C - 25°C.

The efficiency of alternate growth media was evaluated. Initially, dilutions (1:2, 1:5, 1:10, 1:50) of the conventional

Table 7 Microbial Plate Counts on Standard Plate Count Media
after 2, 5, 7 or 10 days of Incubation at 35°C or
20-25°C

Distribution Water Sample No.	35°C			20° to 25°C			
	2 days	5 days	7 days	2 days	5 days	7 days	10 days
1	4	50	--	--	--	--	--
2	2	--	119	--	--	--	--
3	2	--	138	--	--	--	--
4	--	--	--	19	21	43	43
5	--	--	--	34	--	205	205
6	--	--	--	67	--	297	298
7	--	--	--	75	--	322	325
8	185	201	--	234	270	--	--
9	189	207	--	270	370	--	--
10	291	304	--	261	324	--	--
11	--	--	--	457	690	690	--
12	--	--	--	560	--	1456	1456
13	--	--	--	40	151	1832	1832
14	--	--	--	31	140	1922	1922
15	--	--	--	124	149	195	195
16	--	--	--	288	288	312	333

standard plate count medium were tested. the bacterial densities observed in University of Missouri-Columbia tap water and the pipe loop water samples are shown in Table 8. Macroscopic observation of microbial growth characteristics indicated that colonies grown on 1:2 or 1:5 dilutions of standard plate count media were larger than those on other dilutions. Extending the incubation period to seven days resulted in a 40 percent increase in the count observed in medium diluted 1:2. Using water samples from the experimental pipe loop system, colony counts were highest after 2 and 7 days incubation period on medium diluted 1:5.

Other growth media evaluated were basal mineral medium with glucose (0.5%), polypeptone phosphate agar, trypticase soy agar, Middlebrook and Cohn agar and nutrient agar. The microbial colonies cultured on these media were generally similar to those grown on standard plate count medium. Again, growth of microorganisms on these media was found to be better at lower incubation temperatures (20° - 25°C).

These limited studies with a number of growth media have indicated that the standard plate count medium is acceptable for enumerating the microbial population of organisms residing in distribution systems, provided that incubation temperatures are lowered to 20°-25°C and incubation time extended to 5-7 days.

Evaluation of Water Quality in Selected Missouri Water Distribution Systems

Sampling and analytical methods were tested in a number of Missouri cities which had reported water quality changes in their distribution systems. These cities included Moberly, Macon, Chillicothe, Kansas City, Marshall and Columbia.

The results of chemical analyses of hydrant flushing samples are presented in Table 9. Since the chemical oxygen demand (COD) values obtained were below the level of detection, they were not included in the results. However, total organic carbon (TOC) varied from 2.0 to 6.6 mg/l. Moberly, Macon and Marshall water samples ranged in pH from 7.4 to 7.8 whereas Kansas City, Chillicothe and Columbia exhibited pH readings in the range of 8.1 to 9.2. All water samples had residual chlorine at the time of sampling, ranging from 0.2 mg/l (Marshall) to 1.4 mg/l (Columbia). While dissolved oxygen was not measured in all samples, a few hydrant samples were found to have low oxygen contents.

Most of the hydrant samples exhibited low concentrations of total iron (0.1 - 0.2 mg/l). However, the iron concentration of water samples from Moberly was high (0.7 mg/l). Hydrogen sulfide was not detected in any of the hydrant samples taken. As expected, the alkalinity and hardness of water samples from

Table 8 Colony Counts Observed in UMC Tap Water and Pipe Loop Water on Standard Plate Count Medium Diluted 1:2, 1:5, 1:10 and 1:50

Sample/ Incubation Time	Standard Plate Count*				
	Undiluted	Medium Dilution			
		1:2	1:5	1:10	1:50
UMC Tap Water					
2 days	2600	2600	2800	1700	1600
	2400	2400	1600	1300	1900
7 days	5300	7000	6600	6400	2600
	4000	6200	3100	2000	5200
Pipe Loop System Water					
2 days	2900	7300	8500	6900	9600
	8000	6800	8500	6500	4500
7 days	4400	10200	12100	10100	12700
	9600	8700	12700	9800	6700

*Final agar concentration adjusted to 1.0 percent

Table 9 Analysis of Water Distribution System Hydrant
Flushing Samples (August, 1976).

City & Sample No.	pH	Total Chlorine mg/l	Dissolved Oxygen mg/l	Total Iron mg/l	Alkalinity meq/l	Total Hardness meq/l	Turbidity NTU	Total Organic Carbon, as C mg/l	Temp. °C	Raw Water Source
Moberly 1	7.7	0.2	0.1	0.7	4.0	3.4	17.0	6.6	22	Lake
Macon 2A	7.8	0.2	NM	0.1	2.5	2.8	1.4	5.6	21	Lake
2B	7.4	0.6	0.1	0.1	1.8	2.8	4.3	5.6	24	-
Chillicothe 3	8.1	0.2	7.2	0	1.0	1.4	0.2	3.9	25	Well/ River
Kansas City 4A	9.1	1.0	8.2	0	1.1	2.6	6.1	3.1	26	River
4B	9.1	1.1	0.0	0	1.2	2.6	0.7	2.0	25	-
4C	9.2	0.8	6.9	0	1.3	2.5	0.9	2.0	25	-
4D	9.2	0.5	NM	0.1	1.7	2.5	7.7	2.3	26	-
Marshall 5A	7.7	0.4	NM	0.2	3.0	2.4	10.0	2.6	24	Well
5B	7.6	0.2	0.5	NM	2.9	2.5	1.7	4.5	24	-
Columbia 6A	8.8	1.4	9.2	0.1	2.4	3.0	8.8	4.6	20	Well
6B	8.8	0.9	3.8	0.2	3.2	3.0	20.0	3.7	24	-

surface water sources were lower than those from well water sources. Overall, the single, "grab" samples utilized in this study were not adequate to permit the observation of significant water quality changes in the distribution system. This experiment, however, tested the methodology for field sampling of water distribution systems.

The results of the microbiological analyses are presented in Table 10. Although the TOC of the hydrant flushing samples were less than 7 mg/l, a variety of heterotrophic organisms were detected in all water samples. Positive cultures of heterotrophs were confirmed by subculturing into isolation medium, tryptone-glucose agar. A number of isolates were detected in all of the water systems. These were both pigmented (yellow and orange) and non-pigmented organisms which did not grow well in the subculturing medium. Many of the yellow-pigmented organisms were pleomorphic in cellular morphology. Upon longer incubation on the complex medium, giant cells were observed in some cultures. Cellular morphology was not a reliable criteria since even pure cultures sometimes displayed polymorphic characteristics.

Actinomycetes were detected in water samples from Kansas City, Marshall and Columbia, Missouri. Columbia water samples had yeast isolates which precipitated iron hydroxide in ferric ammonium citrate medium. Sulfate-reducing organisms were present in both Kansas City and Marshall, Missouri, water samples. Stalk-forming organisms grew as a thin film on the surface of the nitrifying bacteria enrichment culture media. Initial attempts to isolate a pure culture form of nitrifying bacteria on silica gel solid media were unsuccessful. Thiobacillus was detected in Moberly and Columbia water samples. Nitrogen-fixing heterotrophs were found in Moberly, Macon, Marshall and Columbia water samples. All water samples showed positive growth in thioglycollate anaerobic bacteria enrichment culture media. Spore-forming bacilli were confirmed on direct microscopic examinations.

The results of these preliminary chemical and microbiological analyses indicated that water quality problems might possibly be related to microbial growth in the distribution systems. However, more intensive sampling programs were necessary in order to determine the significance of these observed microorganisms to water quality problems in distribution systems.

Public Water Supply District No. 4, Water System

Figure 4 shows the schematic of the Public Water Supply District No. 4 (PWSD No. 4) distribution system. Fourteen sampling sites and the area of water quality deterioration and resultant consumer complaints are also shown in Figure 4.

Table 10 Microbiological Evaluation of Water Distribution System Hydrant Flushing Samples (August, 1976)

City and Sample No.	Aerobic Organism	Anaerobic Organism	Nitrogen-Fixer	Sulfate-Reducers	Sulfur Oxidizers	Iron Bacteria	Stalked/Budding Bacteria	Actinomycetes	Yeasts
Wheeler 1	+	+	+	+	+	+	+	-	+
Macan 2A	+	+	-	MM	-	+	+	-	MM
Macan 2B	+	+	+	MM	-	+	+	-	MM
Chillicothe 3	+	+	-	MM	-	-	-	-	MM
Kannan 4A	+	+	-	+	-	-	+	+	MM
Kannan 4B	+	+	-	+	-	-	+	+	MM
Kannan 4C	+	+	-	+	-	-	+	+	MM
Kannan 4D	+	+	-	+	-	-	+	+	MM
Marshall 5A	+	+	+	+	-	+	+	+	MM
Marshall 5B	+	+	-	+	-	+	+	+	MM
Columbia 6A	+	+	+	MM	-	-	-	+	+
Columbia 6B	+	+	+	MM	+	+	-	+	+

+: Growth
-: No Growth

MM: Not Measured

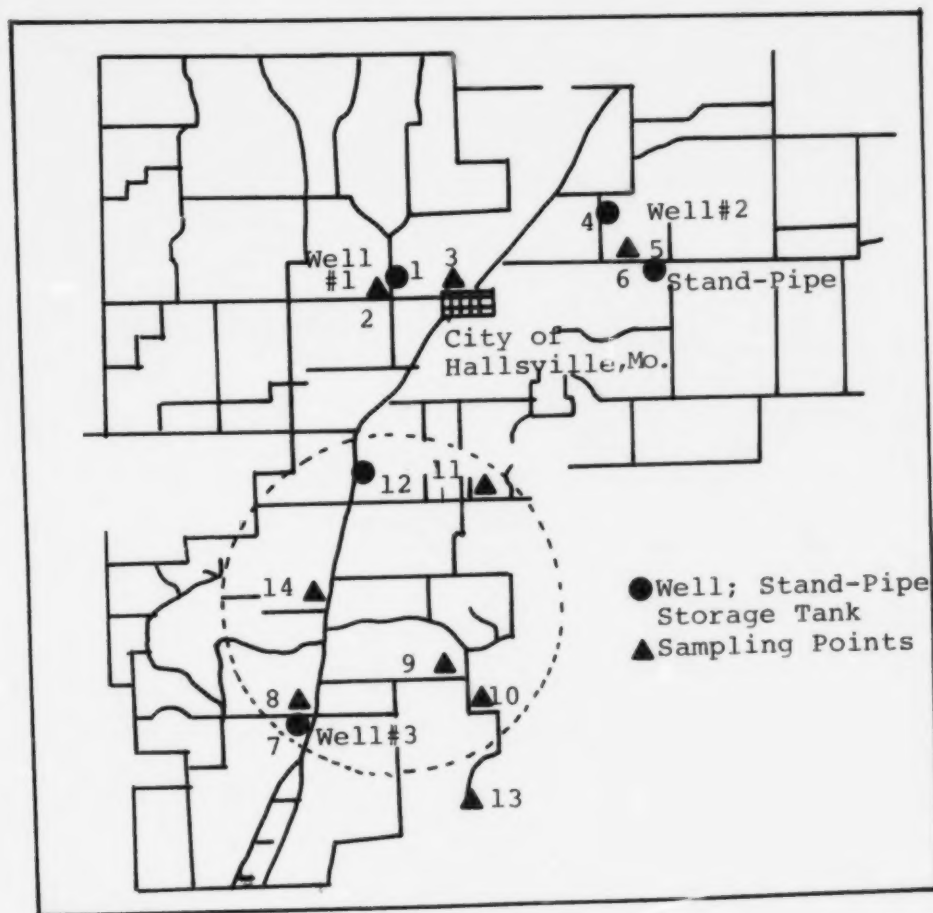


Fig. 4 Schematic of Public Water Supply District No. 4 Distribution System.. Circled area is water quality problem area.

Chemical analyses of water samples from the PWSD No. 4 are summarized in Table 11. Generally, chlorine residuals of water samples were low, particularly in those samples which were collected from the locations of consumer complaints (Figure 5). High total iron concentrations were found at several locations in the district when quality problems were reported (Sample location No. 2, 9 and 12) (Figure 6).

Although sample location No. 2 was only about 100 feet from Well No. 1, approximately a ten-fold increase in iron concentration was observed. Since the distribution main between the two locations was made of cast iron, the observed high iron concentration at Sample location No. 2 is attributed to pipe corrosion. A significant reduction in chlorine residuals was also evident in water samples from sample point No. 2.

Sample location No. 12 was at the hydrant connected to a storage tank near Well No. 3. This hydrant had not been flushed for sometime when the first sampling was conducted. As a result, when water samples were collected, more than five minutes of flushing time was required. Thereafter, water quality became comparable to that found in the distribution main.

Sample location No. 9 was at the residence most severely afflicted with black water problems. The service line for this residence is made of galvanized iron. Water samples were collected from both cold and hot water taps and at the water meter. The results of water analyses indicated significant iron and sulfide concentrations at the household taps while those at the meter were low. The increase in total iron concentrations in the resident tap water samples was attributed to the corrosion of galvanized pipes. In the late spring, when Well No. 1 was not in service, water samples were taken from the district. The iron concentration of samples from Well No. 1 was significantly higher than those previously observed. Otherwise, iron concentrations in the distribution system were relatively low.

Since numerous consumer complaints were about "black" water problems, black sediments were examined and hydrogen sulfide concentrations were monitored. Samples of black sediments were dissolved in nitric acid and analyzed by atomic absorption spectrophotometry. The analyses of the precipitates indicated the presence of copper and iron sulfides. The total dissolved sulfide concentrations of water samples from the PWSD No. 4 are shown in Figure 7. Dissolved sulfide was detected in all water samples, including the well waters. The highest concentrations of sulfide were observed during the spring when total iron concentrations were below 0.1 mg/l.

The sulfate in concentrations of well water No. 1 and No. 2 were slightly higher than that of Well No. 3. As a result,

Table 11 Chemical Analyses of Water Samples from Public Water District NO. 4

Sample No. & Locations	Date of Sampling	pH	Total Dissolved Sulfide mg/l	Total Iron mg/l	Chlorine Residuals Free mg/l	Chlorine Residuals Total mg/l	Dissolved Oxygen Concentration mg/l	Sulfate Ions mg/l	Alkalinity meq/l	Hardness mg/l as CaCO ₃
1 Well No. 1	10/26/76	7.2	0.0	0.03	<0.1	0.1	NM	32	7.9	336
	10/26/76	7.2	0.0	0.03	0.0	0.0	NM	34	8.0	346
	11/4 /76	7.4	0.0	0.06	<0.1	0.1	NM	32	7.9	336
	11/4 /76	7.4	0.0	0.06	0.0	0.0	NM	27	8.0	334
	1/3 /76	7.6	+	0.02	0.0	0.0	NM	NM	6.2	276
	2/25/77	7.5	2.8	0.01	1.1	1.2	NM	NM	7.8	336
	2/25/77	7.4	0.0	0.01	0.0	0.0	NM	35	7.8	352
	3/16/77	7.9	6.1	0.02	0.8	0.9	1.5	36	7.8	NM
2 Fire Hydrant	2/25/77	7.5	2.8	0.75	0.3	0.4	NM	26	7.8	336
	3/16/77	7.9	6.4	0.55	0.6	0.6	NM	35	8.0	NM
3 Resident	2/25/77	7.4	3.2	0.04	0.4	0.5	NM	35	7.7	336
4 Well No. 2	10/26/76	7.2	0.0	0.08	0.0	0.0	NM	34	6.8	316
	11/4 /76	7.3	0.0	NM	0.0	0.0	NM	27	7.0	306
	2/25/77	7.2	1.6	0.03	0.0	0.6	NM	37	6.7	324
	2/25/77	7.3	0.0	0.04	0.0	0.0	NM	34	6.8	316

NM: Not Measured

Table 11 Chemical Analyses of Water Samples from Public Water District NO. 4 (con't)

Sample No. & Location	Date of Sampling	pH	Total Dissolved Sulfide mg/l	Total Iron mg/l	Chlorine Residuals Free mg/l	Chlorine Total mg/l	Dissolved Oxygen Concentration mg/l	Sulfate Ions mg/l	Alkalinity meq/l	Hardness mg/l as CaCO ₃
5 Resident	2/25/77	7.3	2.8	0.08	0.0	0.0	NM	36	6.8	308
6 Standpipes	2/25/77	7.6	0.0	0.10	0.0	0.1	NM	36	10.7	500
	3/16/77	8.1	7.3	0.01	0.0	0.0	NM	33	5.9	NM
	3/16/77	8.0	1.9	0.02	0.0	0.0	NM	31	5.0	NM
7 Well No. 3	10/26/76	7.2	0.0	0.25	0.0	0.0	NM	30	6.3	300
	11/ 4/76	7.7	0.0	0.40	0.0	0.0	NM	32	6.4	298
	2/25/77	7.5	0.0	0.36	0.0	0.0	NM	27	6.3	304
8 Hydroneumatic Tank	10/26/76	7.2	0.0	0.10	0.0	0.0	NM	36	6.5	300
	2/25/77	7.7	0.0	0.12	0.0	0.0	NM	27	6.3	296
9 Resident	10/26/76	7.2	0.2	1.00	0.0	0.0	NM	28	7.8	350
	1/ 3/77	7.4	0.2	0.35	0.0	0.0	NM	NM	6.2	268
	3/16/77	7.9	1.6	0.55	0.0	0.0	1.2	37	8.0	NM
	Hot: 10/26/77	6.9	0.0	0.40	0.0	0.0	NM	NM	6.2	320
	1/ 3/77	7.2	<0.1	0.35	0.0	0.0	NM	NM	5.1	224
	3/16/77	7.7	1.6	0.45	0.0	0.0	NM	40	7.0	NM
	1/ 3/77	7.3	0.0	0.02	0.0	0.0	NM	NM	6.6	274

NM: Not Measured

Table 11 Chemical Analyses of Water Samples from Public Water District NO. 4 (con't)

Sample No. & Location	Date of Sampling	pH	Total Dissolved Sulfide mg/l	Total Iron mg/l	Chlorine Residuals Free mg/l	Chlorine Residuals Total mg/l	Dissolved Oxygen Concentration mg/l	Sulfate ions mg/l	Alkalinity meq/l	Hardness mg/l as CaCO ₃
10 Resident Cold: 11/ 4/76	1/ 3/77	7.3	0.0	0.33	0.0	0.0	NM	33	8.0	320
	3/16/77	7.4	0.0	0.02	0.0	0.0	NM	NM	6.3	304
	Hot: 11/ 4/76	7.6	6.3	0.03	0.3	0.4	2.7	36	7.9	NM
	1/ 3/77	7.3	0.0	0.07	0.0	0.0	NM	33	7.2	304
11 Resident Cold: 1/ 3/77	3/16/77	7.6	2.1	0.02	0.0	0.0	NM	NM	6.3	288
	1/ 3/77	7.4	0.0	0.04	0.0	0.0	NM	36	6.9	NM
	Hot: 1/ 3/77	7.4	2.0	0.01	0.0	0.0	NM	NM	6.5	280
	3/16/77	7.6	0.0	0.04	0.0	0.0	3.9	36	7.7	NM
12 Storage Tank	2/25/77	7.9	3.5	0.01	0.0	0.0	NM	36	6.1	220
	2/25/77	7.6	0.4	1 +	0.0	0.0	NM	36	8.1	NM
	2/25/77	7.2	NM	0.25	0.0	0.0	NM	38	7.5	336
	3/16/77	8.1	1.9	0.34	0.0	0.0	NM	39	7.7	NM
13 Valve @ PWSID #2	3/16/77	7.8	NM	0.25	0.0	0.0	NM	35	7.7	NM
	2/25/77	7.2	0.0	0.04	0.0	0.0	NM	35	7.8	NM
14 Resident	3/16/77	7.8	5.7	0.00	0.1	0.1	NM	38	7.9	332
							1.1	34	7.9	NM

NM: Not Measured

Table 11 Chemical Analysis of Water Samples from PWSD
#4 (con't) (June 7, 1977)

Sample	Alkalinity mg/l	Hardness mg/l	Sulfate mg/l	Total Dissolved Sulfide mg/l	Chlorine Free mg/l	Residual Combined mg/l	Total Iron mg/l	Nitrate mg/l	NI ₃ -N mg/l	TOC mg/l
1	7.8	340	28	1.4	0	0	0.4	0.2	0.2	6.6
2	5.8	276	30	12	0	0	0.1	NM	0.7	5.0
3	6.8	332	31	1.4	0	0	0.1	0.2	0.6	4.9
4	7.8	320	32	1.2	0.7	0	0.1	0.5	1.0	5.3
6	6.6	324	31	1.2	0	0.2	0.1	0.2	1.0	4.9
7	5.9	240	24	1.2	0	0	0.1	0.4	0.7	4.9
8	5.8	284	21	1.4	0	0	0.1	nm	0.3	4.8
11	6.4	294	30	1.2	0	0.1	0.1	0.4	0.5	4.9
12	6.7	320	32	1.4	0	0	0.1	1.6	0.5	4.5
14	6.7	300	30	1.0	0.1	0.4	0.1	1.8	0.5	4.7

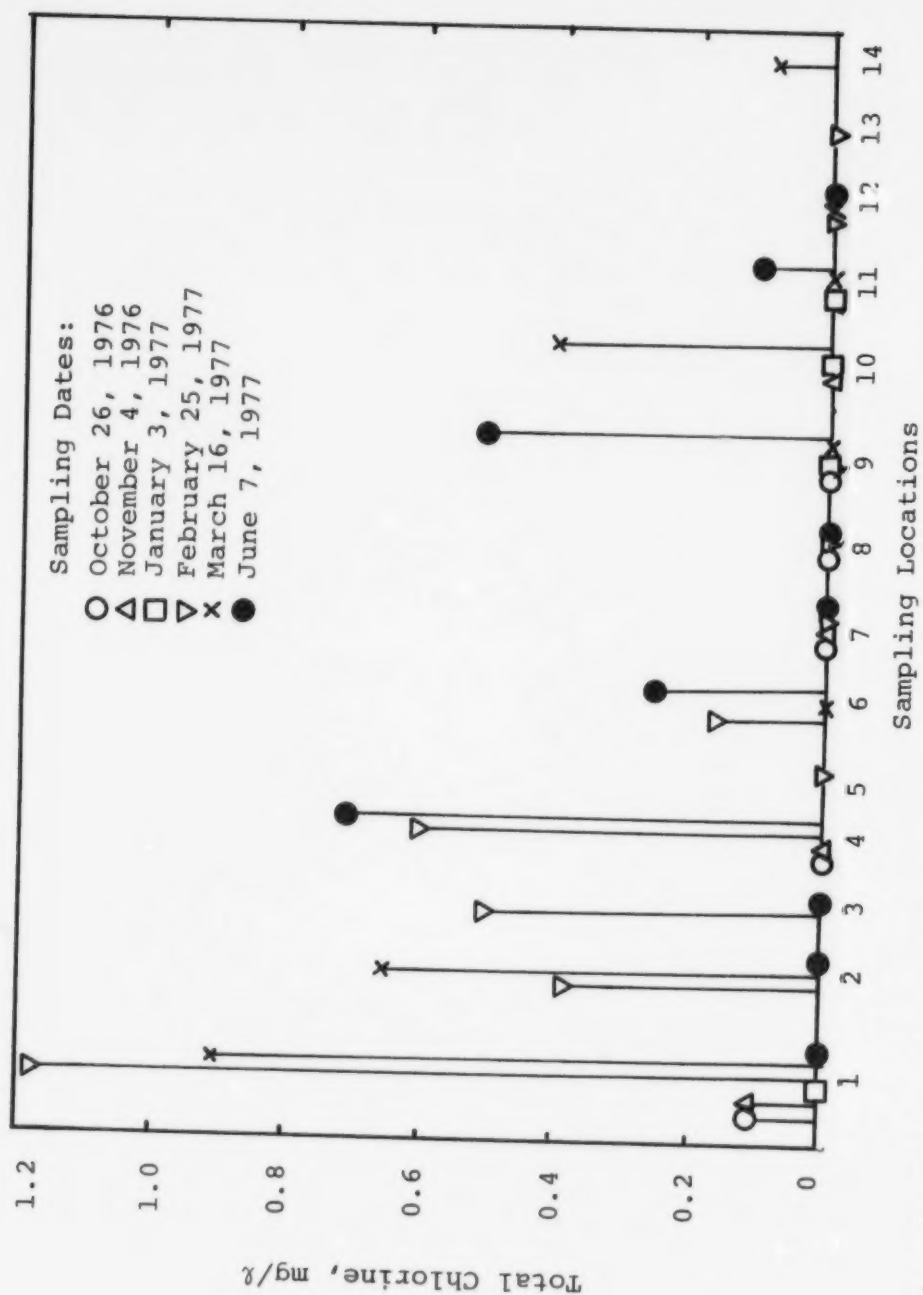


Fig. 5 Total Chlorine Residuals in Water Samples from Public Water Supply District No. 4 Distribution System

Sampling Dates

- October 26, 1976
- △ November 4, 1976
- January 3, 1977
- ▽ February 25, 1977
- × March 16, 1977
- June 7, 1977

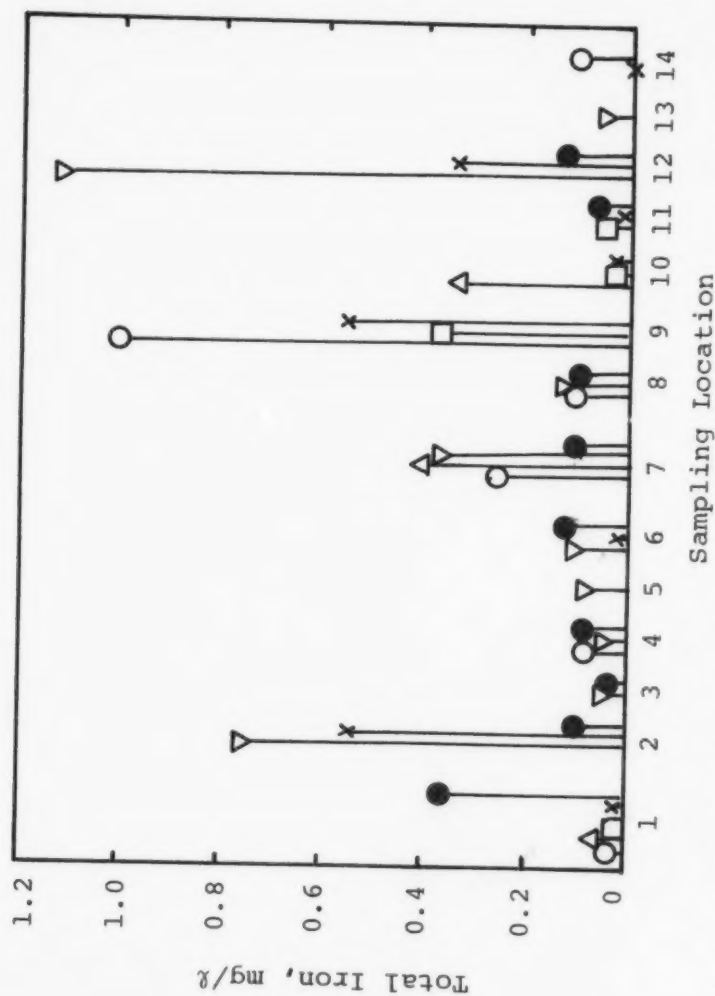


Fig. 6 Total Iron in Samples from Public Water Supply District No. 4 Distribution System

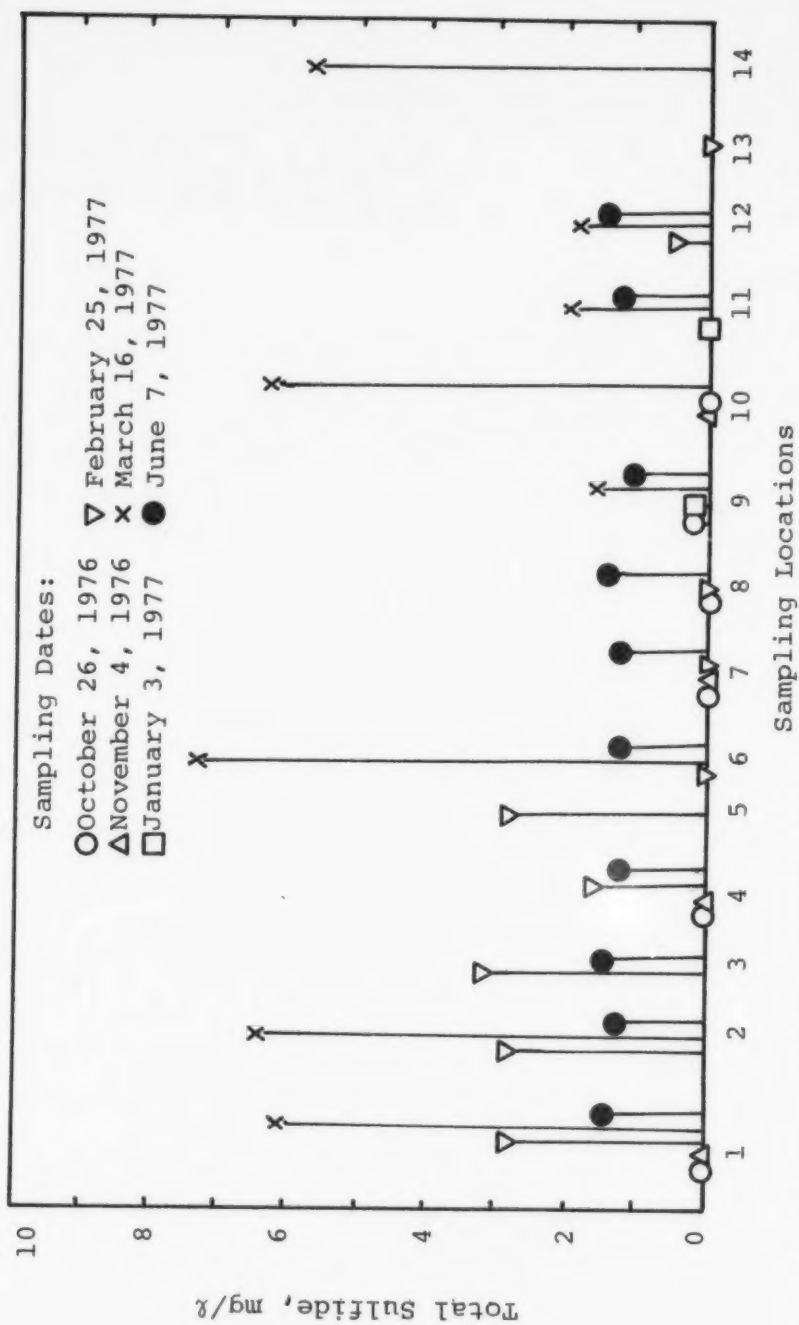


Fig. 7 Total Sulfide Concentration in Water Samples from Public Water Supply District No. 4 Distribution System

slight changes in the sulfate ion concentration could not be observed. Similarly, pH, alkalinity and hardness values in water samples varied randomly. Total organic carbon concentrations were higher in samples taken in the spring. Data were insufficient for evaluating the changes in the forms of nitrogen in water. The principal chemical water quality change observed was the change in the concentration of dissolved sulfide. Iron was apparently contributed both by the well water sources and the corrosion of cast iron and galvanized iron pipes. The result was the formation of iron sulfide, as black precipitates, in the distribution system.

The results of microbiological analyses are summarized in Table 12. Again, a variety of microorganisms were detected in the water samples. The organisms including sulfate-reducing, sulfur-precipitating/oxidizing, iron-precipitating, nitrogen-fixing, nitrifying, denitrifying, yeast and stalk-producing organisms.

It was evident that microorganisms particularly, the sulfur and iron-transforming organisms in the PWSD No. 4 distribution system originated in the well waters. When the February and March samples were taken, Well No. 3 had resumed operation. Its operation had been interrupted for a month previously. Microbiological analyses of Well No. 3 showed the presence of every type of microorganisms investigated above. Similarly, when the samples were collected in June 1977, Well No. 1 was not in operation. The examination of various groups of microorganisms indicated the presence of sulfur and iron-transforming organisms in Wells No. 1 and 3. These observations implied that microorganisms found in the PWSD No. 4 water distribution mains may have proliferated in Wells No. 1 and 3 when they are not in operation. The subsequent infestation of these organisms was evident from observations of their presence in distribution system samples, particularly in samples taken from consumer complaint areas (Sample locations No. 2, 6, 9 and 12).

The activities of sulfur and iron transforming microorganisms in problem areas were indicated by the presence of "black" precipitates. Sulfate-reducing organisms might have reduced sulfate to sulfide, while iron-precipitating organisms precipitated ferric hydroxide. In some portion of the distribution mains sulfide may have formed iron sulfide with the residual iron.

The proliferation of nitrogen transforming organisms was not readily apparent since their activities could not be directly attributed to water quality changes. Their significance was that the presence of nitrogen-fixing organisms might imply an additional source of ammonia, as a nitrogen source for other microorganisms.

Table 12 Microbiological Analysis of Water Samples from the
Public Water District NO. 4 Water Distribution System

Sample & Date	Modified Standard Plate Count Number/ml	Sulfate- Reducing Organisms	Sulfur- Oxidizing Organisms	Iron Pre- cipitating Organisms	Nitrifying Organisms	Nitrogen Fixing Organisms	Denitrifying Organisms	Stalk- Producing Organisms
1) Well No. 1								
2/25/77	1	-	-	-	NM	+	NM	+
3/16/77	1	-	-	-	NM	-	-	-
6/ 7/77	TMC	+	+	+	-	+	-	-
2) F.H. 444. U.								
2/25/77	1	+	+	+	NM	+	NM	+
3/16/77	1	+	+	+	NM	-	+	+
6/ 7/77	15	+	+	+	+	+	+	+
3) Residences								
2/25/77	12	+	+	+	NM	+	NM	+
6/ 7/77	1	+	+	+	-	-	-	+
4) Well No. 2								
2/25/77	1	-	-	-	NM	+	NM	+
6/ 7/77	1	-	-	-	-	-	-	-

+: Positive Detection; -: Negative Detection; NM: Not Measured

Table 12 Microbiological Analysis of Water Samples from the
Public Water District NO. 4 Water Distribution
System (con't)

Sample & Date	Modified Standard Plate Count	Sulfate- Reducing Organisms	Sulfur- Oxidizing Organisms	Iron Pre- cipitating Organisms	Nitrifying Organisms	Nitrogen Fixing Organisms	Denitrifying Organisms	Stalk- Producing Organisms
5) Residence								
2/25/77	80	-	+	+	NM	+	NM	+
6) F.H. @ Standpipe								
2/25/77	6	+	+	+	NM	+	NM	+
3/16/77	12	+	+	+	NM	+	+	+
6/ 7/77	57	+	+	+	-	-	-	+
7) Well No. 3								
2/25/77	47	+	+	+	NM	+	NM	+
6/ 7/77	167	+	+	+	-	-	-	+
8) Hydraulic Tank								
2/25/77	76	+	+	+	NM	+	NM	+
6/ 7/77	1	+	+	+	-	-	-	-
9) Residence								
3/16/77 - Cold	77	+	+	+	NM	+	+	+
3/16/77 - Hot	31	-	+	-	NM	+	NM	-
6/ 7/77	1	-	+	-	-	-	-	-

+: Positive Detection; -: Negative Detection; NM: Not Measured

Table 12 Microbiological Analysis of Water Samples from the
Public Water District NO. 4 Water Distribution
System (con't)

Sample & Date	Modified Standard Plate Count Number/ml	Sulfate- Reducing Organisms	Sulfur- Oxidizing Organisms	Iron Pre- cipitating Organisms	Nitrifying Organisms	Nitrogen Fixing Organisms	Denitrifying Organisms	Stalk- Producing Organisms
10) Residence								
3/16/77 - Cold	1	-	-	+	NM	+	+	-
3/16/77	136	-	+	+	NM	+	NM	-
11) Residence								
3/16/77 - Cold	1	-	-	-	NM	-	+	-
3/16/77 - Hot	1	-	-	-	NM	-	NM	-
6/7/77	41	-	+	-	-	-	-	-
12) F.H. @ Storage Tank								
2/25/77	11	+	+	+	NM	+	NM	+
3/16/77	100	+	+	+	NM	+	+	+
6/7/77	1	+	+	+	-	-	-	-
13) Valve connecting PWS#2								
2/25/77	1	-	-	-	NM	-	NM	+
14) Residence								
3/16/77	1	-	-	-	NM	-	-	-

+: Positive Detection; -: Negative Detection; NM: Not Measured

Another group of microorganism which is indigenous to natural waters includes stalk-producing organisms. Their survival lies in their ability to maintain viability under the adverse condition of low organic concentrations in water. Their importance in inducing water quality changes in distribution system is not readily apparent. However, their ability to form a biological network of flocs may be significantly in establishing a diverse ecological system within the water distribution system.

A number of heterotrophic organisms were isolated from the tryptone glucose medium. They included a variety of Gram negative rods. Many possessed non-diffusible yellow and orange pigments. Many did not grow well in the tryptone glucose medium. Therefore, many isolates would not be subcultured into pure form. Many exhibited pleomorphic cellular morphologies. Several vibrio and spirillum organisms were observed. Generally, microbiological plate counts of water samples in tryptone glucose medium were low (Figure 8).

The majority of water samples exhibited plate counts less than 100 per ml. An attempt to relate bacterial plate counts to chlorine residuals in water was not conclusive, nor could the presence of sulfide in water be related to low bacterial plate counts. Higher bacterial concentrations, however, were associated with water samples which had chlorine residuals less than 0.2 mg/l.

Overall, it is evident that a distribution system can support a wide variety of microorganisms. As a result, water quality changes that are observable in water distribution systems may be linked to growths of diverse communities of microorganisms.

Moberly Water Distribution System

The chemical analyses of a number of water distribution samples are summarized in Table 13. Figure 9 is a schematic of the Moberly, Missouri, water distribution system showing nineteen sampling locations. The areas in which consumer complaints were recorded are designated by circles (locations 8, 12, 14, 15, 18 and 19). The Moberly sampling program spanned the winter and late spring of 1977.

Total iron concentrations are shown in Figure 10. During the late spring (June 14, 1977) iron concentrations were higher (0.3 - 1.4 mg/l) than those measured during the winter (0.0 - 0.62 mg/l). Further increases in iron concentrations were observed in water samples collected from the dead-end main hydrants. At these hydrants, water did not clear completely even after five minutes and flushing. After the initial discharge

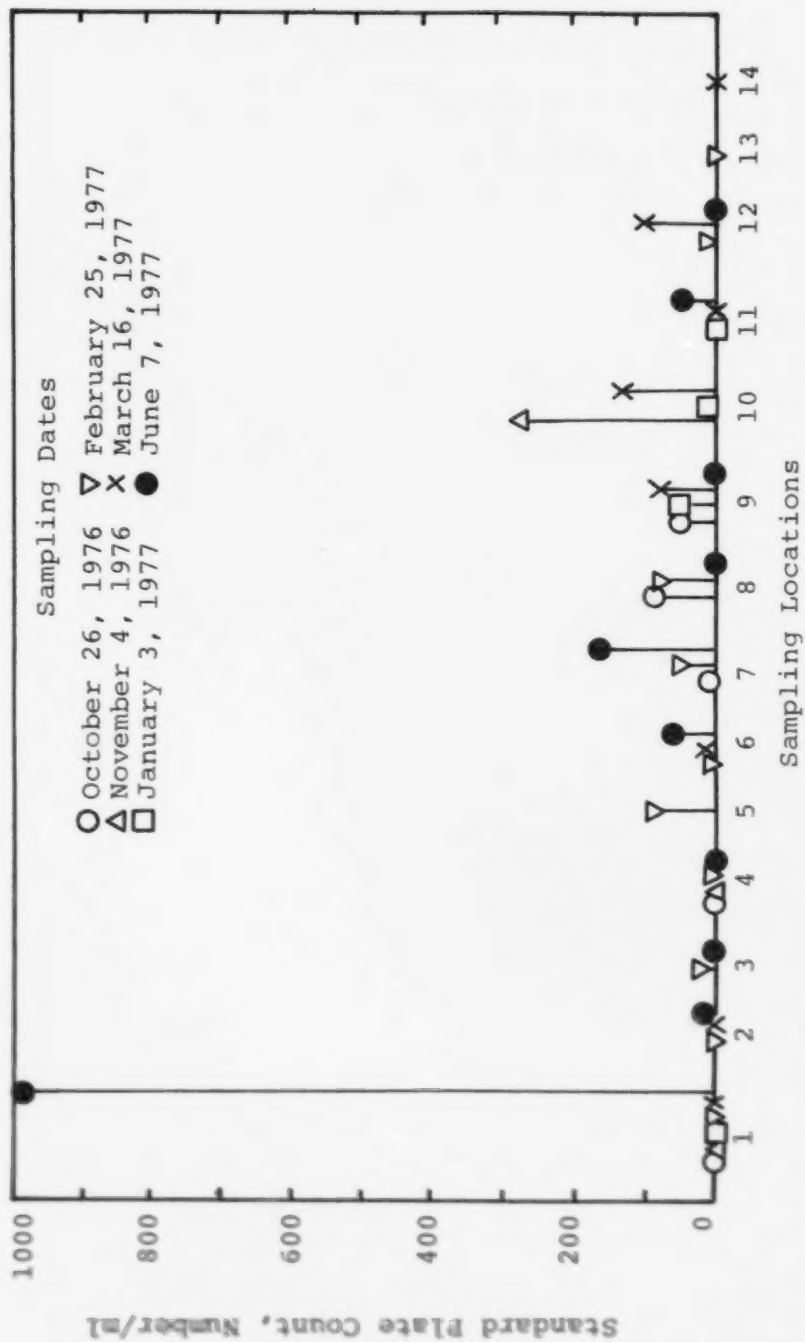


Fig. 8 Standard Plate Counts in Water Samples from the Public Water Supply District No. 4 Water Distribution System

Table 13 Chemical Analyses of Moberly Distribution System Samples

Sample No.	Sampling Dates	pH	Total Dissolved Sulfide mg/l	Total Iron mg/l	Chlorine Residuals Free mg/l	Chlorine Residuals Total mg/l	Dissolved Oxygen Concentration mg/l	Sulfate Ions mg/l	Alkalinity meq/l	Hardness mg/l as CaCO ₃
1	1/12/77	7.8	NM	0.0	0.0	0.0	NM	NM	NM	NM
	2/ 9/77	7.6	NM	0.28	0.0	0.0	NM	29	2.5	NM
	6/ 2/77	7.4	2.4	0.04	0.0	0.0	NM	19	2.2	168
	6/14/77	7.9	0.8	0.80	0.0	0.0	NM	22	2.2	168
2	1/12/77	8.2	NM	0.0	NM	+	NM	NM	NM	NM
	2/ 9/77	7.7	NM	0.0	1.2	1.6	10.4	38	2.7	196
	6/ 2/77	7.6	1.6	0.03	0.2	0.8	NM	24	2.3	160
	6/14/77	7.3	0.2	0.06	0.4	0.7	NM	31	2.1	172
3	2/ 9/77	7.7	NM	0.0	1.4	1.5	10.7	36	2.7	NM
	6/ 2/77	7.2	1.4	0.03	0.3	0.8	NM	26	2.3	172
4	6/ 2/77	7.4	1.4	0.14	0.4	1.0	NM	27	2.3	205
5	6/ 2/77	7.5	1.2	0.04	0.1	0.4	NM	23	2.2	210
	6/14/77	7.7	0.3	0.6	0.0	0.2	NM	25	2.1	172
6	2/ 9/77	8.0	NM	0.01	0.8	1.2	10.3	38	2.7	NM
7	1/12/77	8.3	NM	0.0	NM	+	NM	NM	NM	NM

+: positive detection

NM: not measured

Table 13 Chemical Analyses of Moberly Water Distribution System Samples (con't)

Sample No.	Sampling Dates	pH	Total Dissolved Sulfide mg/l	Total Iron mg/l	Chlorine Residuals Free mg/l	Total mg/l	Dissolved Oxygen Concentration mg/l	Sulfate Ions mg/l	Alkalinity meq/l	Hardness mg/l as CaCO_3
8	1/12/77	8.3	NM	0.0	NM	+	NM	NM	NM	NM
	2/ 9/77	7.8	NM	0.0	0.6	1.0	NM	37	2.7	188
	6/12/77	7.6	1.0	0.05	0.2	0.6	NM	26	2.3	168
9	2/ 9/77	7.9	NM	0.1	0.7	1.2	10.1	38	2.6	196
10	2/ 9/77	8.0	NM	0.01	0.5	0.9	NM	35	2.6	188
10	6/14/77	7.8	0.4	0.0	0.1	0.2	NM	26	2.2	160
11	6/ 2/77	7.6	1.2	0.06	0.0	0.2	NM	21	2.2	184
12	1/12/77	8.5	NM	0.62	NM	+	NM	NM	NM	NM
	2/ 9/77	7.9	NM	0.02	0.9	1.4	11.8	36	2.7	NM
	6/14/77	6.8	0.4	1.4	0.0	0.2	NM	25	2.1	168
13	1/12/77	8.4	NM	0.0	NM	+	NM	NM	NM	NM

+: positive detection

NM: not measured

Table 13 Chemical Analyses of Moberly Water Distribution
System Samples (con't)

Sample No.	Sampling Dates	pH	Total Dissolved Sulfide mg/l	Total Iron mg/l	Chlorine Residuals Free mg/l	Total mg/l	Dissolved Oxygen Concentration mg/l	Sulfate Ions mg/l	Alkalinity meq/l	Hardness mg/l as CaCO ₃
14	6/14/77	7.5	0.6	0.8	0	0.1	NM	24	-	160
15	1/12/77	8.2	NM	0.2	NM	+	NM	NM	NM	NM
	2/ 9/77	8.0	NM	0.4	0.3	0.8	10	40	2.8	NM
	6/ 2/77	7.1	1.0	0.34	0.0	0.2	NM	31	2.4	164
	6/14/77	7.9	0.6	0.3	0.0	0.2	NM	31	2.2	168
16	1/12/77	8.4	NM	0.14	NM	+	NM	NM	NM	NM
	2/ 9/77	7.9	NM	0.01	0.8	1.1	NM	38	2.6	196
17	6/ 2/77	7.4	1.0	0.06	0	0.2	NM	23	2.1	188
18	6/14/77	7.9	0.5	0.9	0	0.2	NM	27	2.2	172
19	2/ 9/77	8.0	NM	0.02	0.3	0.4	NM	36	2.7	NM

+: positive detection

NM: not measured

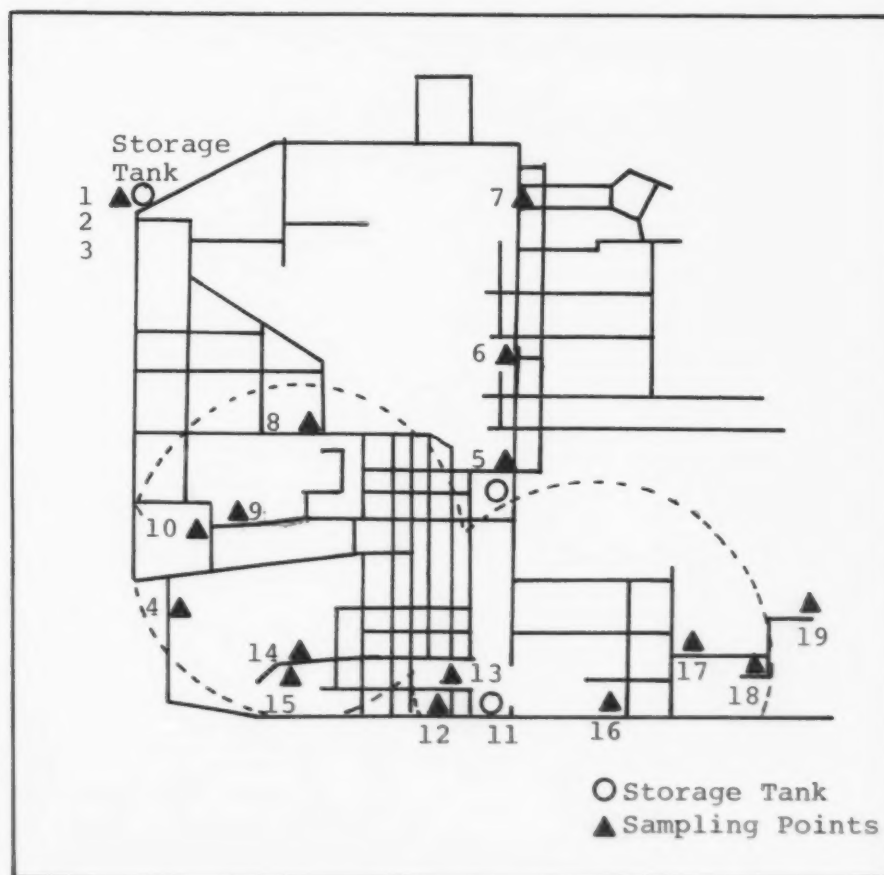


Fig. 9 Schematic of Moberly Water Distribution System.
Circled areas are water quality problem areas.

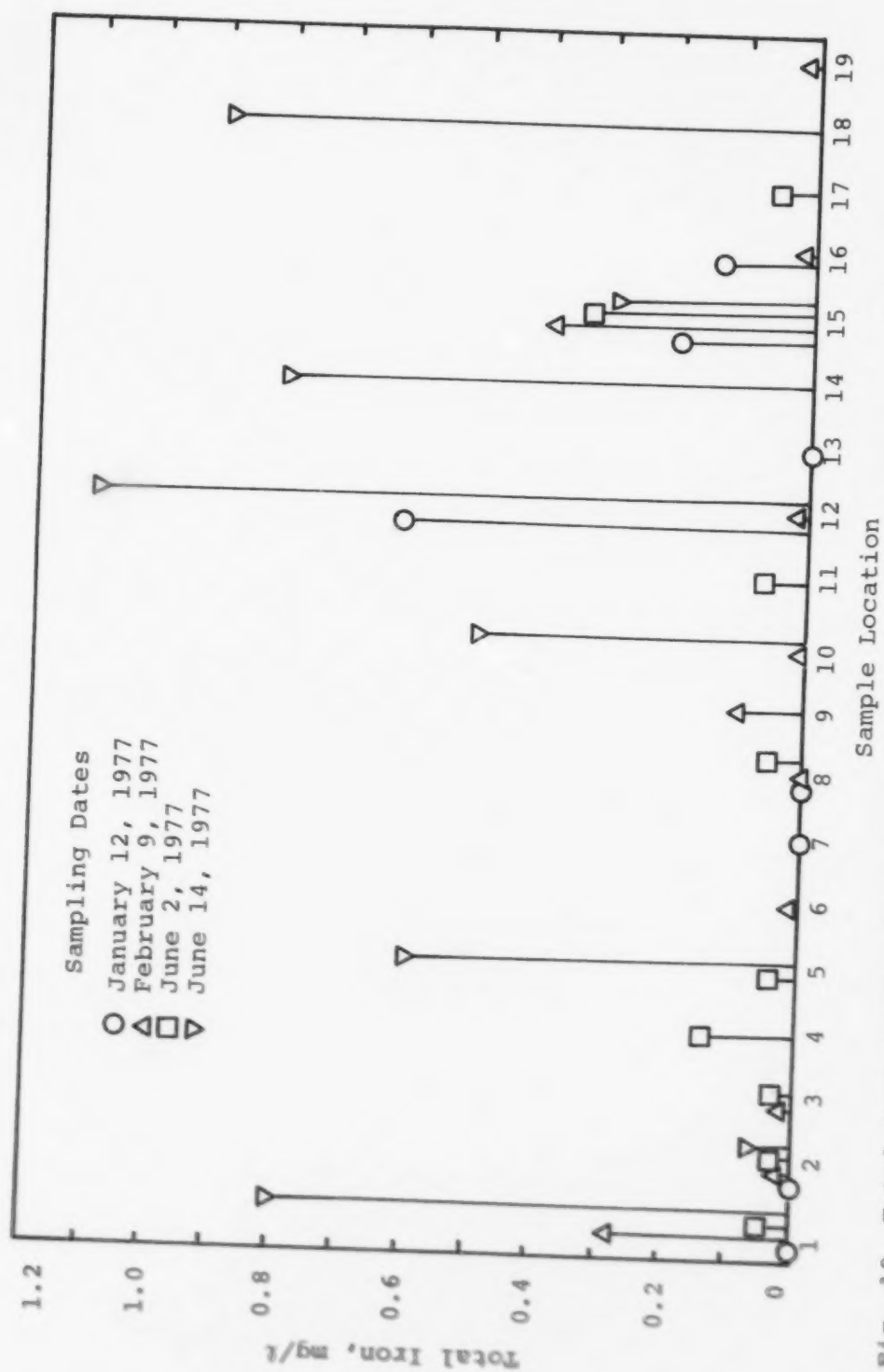


Fig. 10 Total Iron in Samples from Moberly Water Distribution System

of red water, a mixture of grey and brown water was usually discharged in the hydrant flushings.

Other instances of discolored water were reported by residents whose water mains were located near samples sites 5, 14 and 18.

The chlorine residuals of distribution water samples are illustrated in Figure 11. In general, Moberly water exhibited chlorine residuals throughout the system. Reductions in chlorine residuals were observed as the sampling locales became more distant from the treatment plant. An 85 percent decrease in chlorine residual was observed at location 19 when compared to that of the treated water at the treatment plant.

As expected, chlorine residuals in water affected bacterial plate counts in the distribution system. Raw water, without any chlorine residual, contained up to 200 organisms per ml of water, whereas the treated water with chlorine residuals contained less than 5 organisms per ml. When the chlorine residual was above 0.8 mg/l, the plate count ranged from 0 - 20 organisms per ml. In contrast, when the total available chlorine was less than 0.3 mg/l, up to 500 organisms per ml were observed. Often samples from problem area showed still lower chlorine residuals. For instance, the water sample (Sample location No. 14) which had the lowest chlorine residual was from residence with the worst black water problem.

Analysis for dissolved oxygen was conducted throughout the winter. No apparent change was observed within the distribution system.

The pH of the Moberly water showed a seasonal variation. During the winter, the pH of water ranged from 7.7 to 8.5, while during the late spring, the pH of water ranged between 6.8 and 7.9. The largest difference in the pH of water was exhibited at the location No. 12, where the pH of water decreased from 8.5 in the winter to 6.8 in the late spring. The highest nitrate ion concentration (3.4 mg/l as NO_3) was also found in the water sample collected from the location No. 12. These changes in pH and nitrate ions could have resulted from the nitrification reaction as a result of the activity of nitrifying microorganisms. Nitrifying microorganisms were observed in water samples obtained from location No. 12. Since nitrifying organisms prefer a slightly alkaline pH environment, conditions at location No. 12 might have been satisfactory for nitrifying organisms to proliferate during the spring.

Sulfate ion concentrations exhibited a possible seasonal variation. During the water sampling, the sulfate ion concentrations ranged from 21 to 31 mg/l.

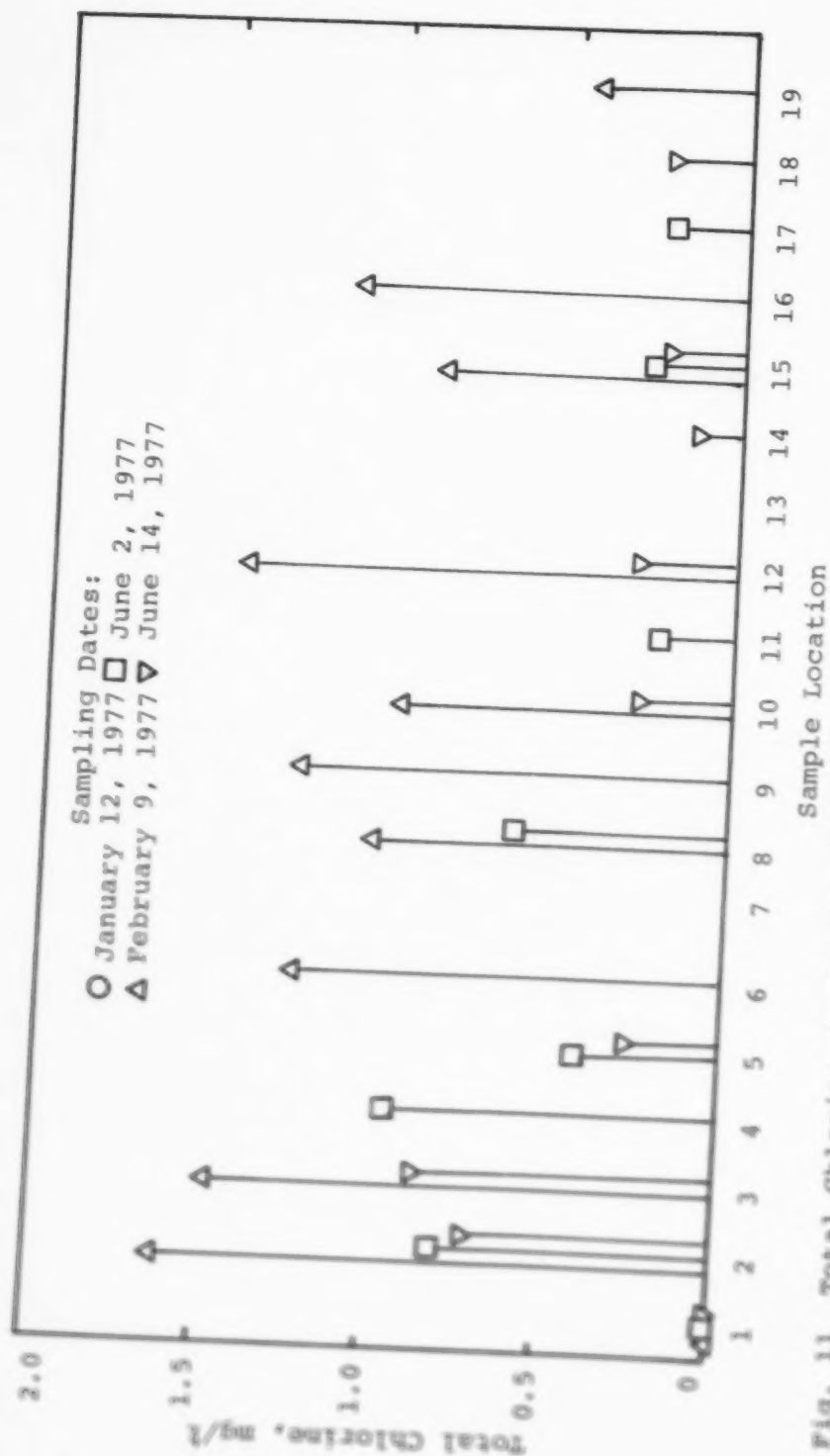


Fig. 11 Total Chlorine in Samples from Moberly Water Distribution System

Repeated observations of sulfate-reducing organisms in both winter and late spring water samples indicated that these organisms maintained their habitat in the original source water. In the Moberly water system, the biochemical reduction of sulfate to sulfide was indicated by the presence of dissolved sulfide and depleted sulfate ion concentrations in waters analyzed in late spring.

Other water quality parameters including alkalinity, hardness, phosphate, nitrate and total organic carbon (TOC) were examined only during the late spring of 1977. Notable differences in water qualities were observed between two sampling dates, June 2 and June 14, 1977 for two parameters, nitrate and total organic carbon. The nitrate concentrations of the June 14 water samples were 4 to 10 times higher than those found in the June 2 water samples.

The TOC values of several distribution water samples analyzed in June 2, 1977 were about half of those sampled in June 14, 1977. An anomaly was observed in a water sample obtained from a dead-end main, location No. 15. Its TOC value on June 14, 1977 was 8.3 m/gl as carbon.

Microbiological analyses of Moberly water samples are summarized in Table 14. The bacterial plate counts of water samples were generally low (Figure 12). Only at two locations did samples exhibit bacterial plate counts near 500 per ml. In Moberly, the bacterial plate counts of water samples analyzed in late spring increased significantly. Up to an 86-fold increase in bacterial density was observed at Sample location No. 12.

Geldreich, et al. reported that high bacterial plate counts may adversely effect the detection of coliform organisms in water (96). Although the bacterial densities in the Moberly water system were much lower than the level recommended level by Geldreich and his associates (i.e., less than 500 per ml of water), problems of discolored water were reported at several locations in Moberly, including those at sample location Nos. 8, 11, 12, 15 and 18. In particular, sample location No. 8 was the site of numerous consumer complaints. Yet, at this location the bacterial plate counts were less than five organisms per ml.

A comprehensive microbiological analysis was initiated in order to identify various microbiological populations in the Moberly distribution system. A variety of microorganisms including sulfate-reducing, sulfur-oxidizing, iron-transforming, nitrogen-fixing, nitrifying, denitrifying and stalk-forming microorganisms was observed in hydrant flushing samples. The findings are summarized in Table 14. In general, sulfur and

Table 14 Microbiological Analysis of Water Samples from the
Moberly Water Distribution System

Sample & Date	Modified Bacterial Plate Count (bacteria/ml)	Sulfate- Reducing Organisms	Sulfur- Oxidizing Organisms	Iron Pre- cipitating Organisms	Nitrifying Organisms	Nitrogen Fixing Organisms	Nitrifying Organisms	Stalk- Producing Organisms
1) Raw Water								
1/12/77	10	+	-	+	+	-	NM	+
2/ 9/77	500	+	-	+	+	+	NM	+
6/ 2/77	200	+	+	+	-	-	+	+
6/14/77	2000	+	-	+	-	-	+	-
2) Finished Water								
1/12/77	1	-	-	NM	NM	-	-	-
2/ 9/77	1	-	-	-	-	-	-	-
6/ 2/77	1	-	-	-	-	+	+	-
6/14/77	1	-	-	-	-	+	+	-
3) F.M. & Filtration Plant								
2/ 9/77	1	-	-	+	-	+	-	-
6/ 2/77	11	-	+	-	-	+	-	-
4) F.M. & Secondary & Moberly								
6/ 2/77	0	-	-	+	-	+	+	-

Table 14 Microbiological Analysis of Water Samples from the
Merely Water Distribution System (cont.)

Sample & Date	Modified Standard Plate Count Technique	Sulfate- Reducing Organisms	Sulfate- Oxidizing Organisms	Iron Pro- oxidizing Organisms	Nitrifying Organisms	Nitrogen Fixing Organisms	Nitrifying, Stalk- Producing Organisms
50 Residues, 0 Residues & No. 10							
6/2/77	10	-	+	+	-	-	+
6/16/77	95	-	+	+	-	-	-
60 Residues							
2/3/77	1	-	+	-	100	-	+
70 Residues							
1/11/77	1	-	-	100	100	+	-
80 P.M. 0 Residues & No. 10							
1/11/77	2	+	-	+	100	+	+
2/3/77	1	+	-	+	+	+	+
6/2/77	2	+	+	-	-	-	+
90 P.M. 0 P.M.							
2/3/77	6	+	-	+	100	+	-
100 Residues by Dr. C. C. C. C.							
2/3/77	6	+	-	+	-	+	-
6/16/77	107	-	+	-	-	-	-

Table 10 Microbiological Analysis of Water Samples from the
Moberly Water Distribution System (cont.)

Sample & Date	Modified Standard Plate Count Bacteria/ml	Sulfate- Reducing Organisms	Sulfur- Oxidizing Organisms	Iron Oxide- Oxidizing Organisms	Hetero- fermenting Organisms	Nitrogen Fixing Organisms	Indifferent Organisms	Stalk- Producing Organisms
100 F.M. @ Moberly & Moberly 6/22/77	444	0	0	0	0	0	0	0
100 F.M. @ Clark & Grand 1/12/77	2	0	0	0	0	0	104	0
2/8/77	15	0	0	0	0	0	104	0
6/14/77	172	0	0	0	0	0	0	0
100 Moberly 1/12/77	1	0	0	0	0	0	0	0
100 Moberly 6/14/77	59	0	0	0	0	0	0	0
100 F.M. @ Clark & Grand 1/12/77	2	0	0	0	0	0	104	0
2/8/77	100	0	0	0	0	0	104	0
6/22/77	97	0	0	0	0	0	0	0
6/14/77	85	0	0	0	0	0	0	0

Table 16 Microbiological Analysis of Water Samples from the
Moberly Water Distribution System (con't)

Sample & Date	Modified Standard Plate Count Bacteria/ml	Sulfate- Reducing Organisms	Sulfate- Oxidizing Organisms	Iron Pro- oxidizing Organisms	Hetero- trophic Organisms	Nitrogen Fixing Organisms	Heterotrophic Stalk- Producing Organisms
Moberly, Mo.							
1/13/77	5	+	-	104	104	+	+
2/ 9/77	3	+	+	+	+	+	+
(1) Moberly & Union							
6/ 2/77	470	-	+	+	+	+	+
(10) Moberly & New Madrid							
6/14/77	146	-	+	-	-	+	-
(10) Moberly							
2/ 3/77	254	-	+	+	-	+	+

+: Growth to 5 ml of water sample NM: Not Measured

-: No growth to 5 ml of water sample

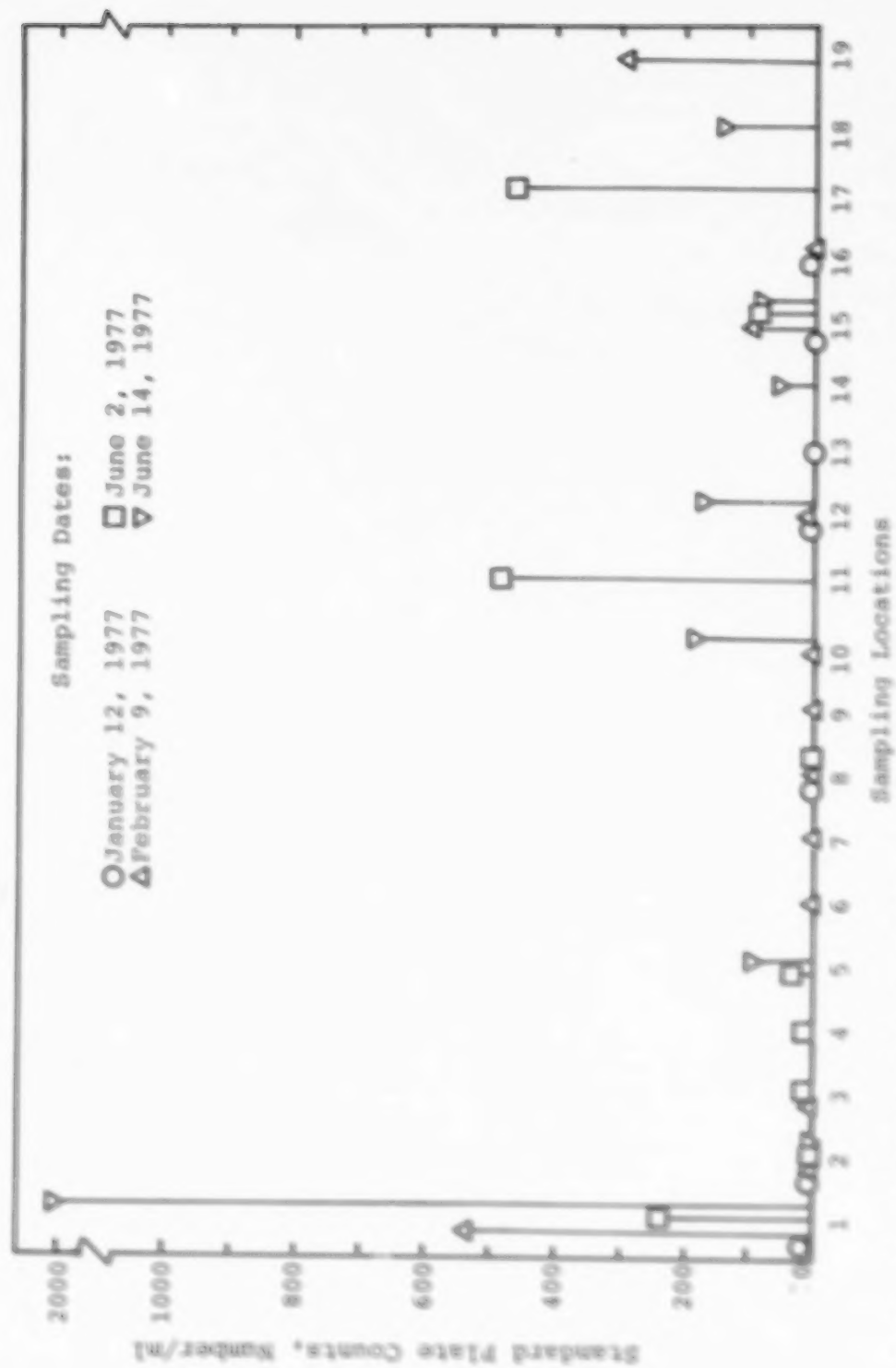
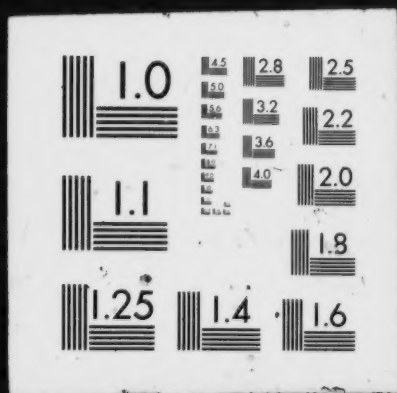


Fig. 12 Standard Plate Counts in Samples from Moberly Water Distribution System

2 0 F 5

P B 8 4

1 5 7 4 9 4



iron-transforming microorganisms were frequently found in locations which had water quality problems. Moreover, water from the dead-ends usually contained the more diverse groups of microorganism, including organisms that constitute the microbiotic cycles of carbon, nitrogen, sulfur and iron. The importance of detecting the diverse speciation of microorganisms in a given habitat is the various microbial interrelationships including natural selection, commensalism, synergism, etc. can maintain a persistent survival of microbial populations. Disinfection of water in these established microbial ecosystem may be more difficult.

In Moberly, problems of discolored water, "red and black", in the distribution system were generally limited to dead-end mains and mains located farthest from the water treatment plant. The iron concentration of the treatment plant finished water was less than 0.1 mg/l. However, iron concentrations as high as 1.4 mg/l were observed at location No. 12. Since the major constituent of Moberly distribution mains was cast iron, the resultant discoloration at several locations was attributed to the corrosion of pipe materials.

The residents near sample location No. 15 were experiencing hydrogen sulfide odors and black water problems in their water, especially during the summer. Sulfate-reduction by microorganisms was indicated by their repeated detection in water samples from location No. 15.

Higher bacterial plate counts and the presence of iron-precipitating organisms were observed in samples from locations No. 17 and 19. The activity of these organisms might have led to consumer complaints by these area residents.

In Moberly, the source water had evidently contributed to the microbial populations found in the distribution system. Disinfection by chlorine was effective for most of the distribution systems. However, a number of distribution system sites experienced water quality changes which may have been influenced by activities of a variety of established microbial populations.

Marshall Water Distribution System

The results of chemical analyses of water samples from the Marshall, Missouri, water distribution system are summarized in Table 15. A significant decrease in the total chlorine residuals in water samples collected from the distribution system was observed. The chlorine residual of the finished water was 2.95 mg/l, while in some locations of the distribution system, less than 0.01 mg/l of chlorine residual was observed.

Table 15 Chemical Analyses of Marshall, MD Water Distribution System Samples

Sample Location	pH	Alkalinity mg/l	Hardness mg/l as CaCO ₃	Dissolved Oxygen mg/l	Total Iron mg/l	Chlorine Free mg/l	Chlorine Residuals Total mg/l	Sulfate mg/l	Nitrate mg/l
1 Raw Water	7.4	4.9	224	NM	0.36	0	0	<1	0.5
2 Finished water	7.7	2.3	112	7.6	<0.02	0.07	2.95	<1	0.6
3 Residence	7.5	2.3	116	NM	0.05	0	0.15	3	0.7
4 Residence	7.5	2.3	112	NM	0.02	0	0.21	1	1.0
5 Residence	7.6	2.3	116	6.8	0	0	0.49	4	1.1
6 Residence	7.7	2.5	120	NM	<0.01	0	0.30	3	0.8
7 F.H. a.	7.7	2.5	124	4.6	0	0	<0.01	10	0.7
b.	7.7	2.4	124	NM	0	0	<0.01	10	0.7
8 F.H. a.	7.7	2.4	124	NM	0.04	0	<0.01	4	0.7
b.	7.6	2.4	124	NM	0.06	0	<0.01	4	0.7
9 F.H. a.	7.6	2.4	124	NM	0.01	0	0.12	5	0.8
b.	7.6	2.4	124	5.8	0.18	0	0.20	5	0.8

a. Sample collected after 30 seconds flushing

b. Sample collected after 60 seconds flushing

Dissolved oxygen concentrations were lower in the distribution system samples than in finished plant water. Slight increases in nitrate-nitrogen concentrations were observed in all distribution water samples. Sulfate ion concentrations were observed in all distribution water samples. Sulfate ion concentrations observed in the Marshall distribution system water were low compared to those found in other systems.

The water quality problem in Marshall, Missouri, is mainly the discoloration of water, iron in a certain part of the system (Sample location Nos. 8 and 9). Measurements of total iron concentrations, however, showed only slight increases in the distribution system. Other parameters, pH, alkalinity and hardness, did not change significantly.

The results of the microbiological analyses are presented in Table 16. The standard plate counts of samples of Marshall distribution system water were less than 100 colonies per ml of water. Even the water samples from problem areas showed low bacterial plate counts.

Identifications of other microorganisms indicated the presence of iron-transforming, nitrogen-fixing and stalk-producing microorganisms in most of water samples. Sulfate-reducing organisms were observed only in the problems areas, i.e., at sample locations Nos. 8 and 9. The infrequent occurrence of these anaerobic sulfate-reducing organisms is attributed to the low concentrations of sulfate ions in the raw water. Yeasts and actinomycetes were also observed in distribution system water.

As in the Moberly water system, deterioration of water quality in the distribution system was observed only in the isolated part of the system. The proliferation of both sulfur and iron-transforming microorganisms was evident in the problem areas. The frequent discoloration of water was attributed to the sloughing of iron precipitates that might have accumulated on pipe surfaces after iron-precipitating bacteria had deposited hydrated iron oxides.

Boonville Water Distribution System

The analysis of raw, finished and two selected distribution main samples from Boonville, Missouri, are presented in Table 17. Two locations in the distribution system did not exhibit any water quality problems prior to the sampling time.

The chlorine residuals found in the distribution system were lower than that of the finished water. Nearly 60 percent of the chlorine residual was reduced at the sample point No. 4. When this hydrant was flushed to collect the water sample, more than five minutes of flushing was required before the red color

Table 16 Results of Microbiological Analysis of Marshall, MO Water Distribution System Samples
(Sampling Date: February 9, 1977)

Sample Location	Plate count no./ml 35°C 4hrs.	Sulfate Reducers	Sulfur Oxidizers	Iron Transformers	Nitrogen Fixer	Yeasts/molds	Actino- mycetes	Stalk-prod. organisms
1	10	-	-	+	-	-	+	-
2	3	-	-	-	-	-	-	-
3	61	-	-	+	+	-	-	+
4	63	-	-	+	+	-	-	+
5	30	-	+	+	+	-	+	+
6	8	-	+	+	+	+	-	+
7	58	-	+	+	+	-	-	+
8	64	+	+	+	+	-	-	+
9	17	+	+	+	+	+	+	+

Table 17 Chemical Analysis of Boonville Water Distribution System Samples
(Sampling Date: June 22, 1977)

Sample Location	pH	Alkalinity meq/l	Hardness mg/l as CaCO ₃	Chlorine Residual mg/l		Total Dissolved Sulfide mg/l	Nitrate mg/l	Ammonia mg/l	Total Iron mg/l	TOC mg/l	Total Phosphate mg/l
				Free	Combined						
1	6.8	4.2	168	0.0	0.0	0.8	0.8	-	0.3	7.6	0.09
2	8.2	1.6	152	0.0	1.4	0.0	0.4	0.8	0.0	5.0	0.15
3	8.1	1.6	120	0.0	1.0	0.0	0.1	0.8	0.2	5.4	0.23
4	8.1	1.9	128	0.8	0.4	0.0	0.1	0.7	0.1	5.0	0.05

1 - Raw water

3 - Fire hydrant

2 - Finished water

4 - Fire hydrant

of the water had cleared completely. Only minor variations in pH, alkalinity, hardness, ammonia and the total organic carbon were observed.

Some decreases in the nitrate, iron and phosphate concentrations were observed in the water sample from location No. 4. Microbiological analysis of the Boonville water samples indicated that the water samples with the lowest chlorine residual, Sample location No. 4, contained as large a variety of microorganisms as the raw water (Table 18). These included sulfate-reducing, sulfur-oxidizing, iron-transforming, nitrogen-fixing, denitrifying organisms and yeast. In addition, a definite increase in bacterial plate counts in standard method agar was observed in the distribution system. The small amount of polyphosphate added did not appear to cause any measurable negative effect on water quality parameters, such as TOC, iron and standard plate count.

Columbia Water Distribution System

The results of chemical analyses on four different sampling dates are listed in Table 19. In Columbia, treated water is rechlorinated to attain 2 mg/l chlorine at the pumping station before it is pumped to the distribution system. In the northeastern part of the city some distribution mains frequently receive untreated water directly from the city wells. The quality of water from these city wells is different from the treated water supplied from Columbia's water treatment plant at McBaine.

The thirteen sampling locations employed in the study are shown in Figure 13. Consumer complaints were related to "occasional red water" and taste and odor problems at several locations. At sampling location No. 4, the resident had reported high bacterial plate counts in her water.

The chlorine residuals observed at various locations in the distribution system are shown in Figure 14. Significant losses were observed, particularly, with respect to free available chlorine residuals. Data from the four sampling dates varied within each sampling location. However, mean values at each sample site for the four sampling dates were calculated so that the chlorine residuals could be compared with that applied at the pumping station. A 34 to 97 percent reduction of chlorine residuals in the distribution water samples were observed. In general, those sampling locations where chlorine residuals were found to be less than 50 percent of the applied chlorine concentration were also regions of frequent consumer complaints regarding "red water" and taste and odors. These areas are located at sampling sites Nos. 4, 5, 6 and 10.

Nearly complete (90 percent) reduction of chlorine resi-

Table 18 Microbiological Analysis of Boonville Water Distribution System Samples
(Sampling Date: June 22, 1977)

Sample Locations	Standard Plate Count No./ml	Sulfate Reducers	Sulfur Oxidizers	Iron Transformers	Stalk Producers	Nitrogen Fixers	De- Nitrifiers	Nitrifiers	Yeasts Molds	Hetero- trophs
1	1.0x10 ³	+	+	+	-	+	+	+	-	+
2	3.0x10 ¹	-	-	+	-	-	+	-	-	+
3	3.1x10 ²	+	+	+	-	-	-	-	-	+
4	1.1x10 ²	+	+	+	-	+	+	-	+	+

Samples: 1 - Raw water 3 - Fire hydrant
2 - Finished water 4 - Fire hydrant

Table 19 Chemical Analysis of Columbia Water Distribution System Samples

Sample Location	Date	pH	Alkalinity meq/l	Hardness mg/l	Total Iron mg/l	Chlorine Residual mg/l		NH ₃ mg/l	Nitrate mg/l	Sulfate mg/l	Total Dissolved Sulfide mg/l	Total Phosphate mg/l	TOC mg/l
						Free	Combined						
1	6/28/77	6.8	8.2	372	2.83	0	0	0.7	0.8	-	0.4	0.12	6.8
	7/6/77	6.4	7.6	400	2.97	0	0	-	1.0	60	0.3	0.13	8.1
	7/13/77	-	-	-	2.83	0	0	-	0.2	-	0.3	0.32	7.0
2	8/10/77	7.4	-	-	3.06	0	0	0.3	-	48	0.4	0.01	5.0
	6/28/77	6.9	2.8	172	0.04	1.4	0.1	0.3	0.1	-	0	0.11	6.4
	7/6/77	6.6	2.5	180	0.05	1.5	0.1	0	0	49	0	0.12	6.4
3	7/13/77	-	-	-	0.04	1.1	0.1	-	0	-	0	0.13	-
	8/10/77	8.5	-	-	0.03	1.8	0.2	0.2	-	52	0	0.03	4.9
	6/28/77	7.1	2.2	136	0.17	0.7	0.2	0.4	0	-	0	0.02	4.7
4	7/6/77	7.8	3.1	216	0.15	0.7	0.2	0.2	-	52	0	0.02	4.5
	7/13/77	-	-	-	0.16	1.1	0.2	-	0	-	0	0.25	4.3
	8/10/77	8.1	-	-	0.14	1.1	0.2	0.3	0	50	0	0.06	4.9
5	6/28/77	6.5	2.1	136	0.05	0.6	0.2	0.4	0	-	0	0.07	NH
	7/6/77	7.2	2.1	156	0.05	0.1	0.2	-	0	55	0.1	0.08	5.3
	7/13/77	-	-	-	0.08	0.4	0.1	-	0	-	0	0.09	5.0
6	8/10/77	8.1	-	-	0.10	0.5	0.2	0.3	0	46	0	0.05	4.4
	6/28/77	8.4	-	-	0.10	0.2	0.1	0.2	-	53	0.3	0.14	4.5
	7/6/77	7.3	2.1	144	1.20	0.6	0.1	0.3	0.3	-	0	0.02	5.4
7	7/13/77	-	-	-	1.15	0.8	0.2	-	-	55	0	0.05	4.3
	8/10/77	8.2	-	-	0.02	1.0	0.1	-	0	-	0	0.11	6.8
	6/28/77	7.7	2.2	140	0.15	0.7	0.1	0.3	0	-	0	0.08	4.6
8	7/6/77	7.2	1.8	144	0.35	0.5	0.1	-	0	57	0	0.10	5.7
	7/13/77	-	-	-	0.18	1.1	0.1	-	0	-	0	0.20	8.2

Table 19 Chemical Analysis of Columbia Water Distribution System Samples (cont.)

Sample Location	Date	pH	Alkalinity meq/l	Hardness mg/l	Total Iron mg/l	Chlorine Free mg/l	Residual Combined mg/l	NH ₃ mg/l	Nitrate mg/l	Sulfate mg/l	Total Dissolved Sulfide mg/l	Total Phosphate mg/l	TOC mg/l
9	6/28/77	7.2	2.1	144	0.10	0.7	0.1	0.2	0	-	0	0.04	6.3
	7/ 6/77	7.4	2.4	200	0.15	0.7	0.1	-	0	52	0	0.03	5.1
	7/13/77	-	-	-	0.16	0.7	0.1	-	0	-	0	0.09	11.8
	8/10/77	8.2	-	-	0.12	-	0.1	0.4	-	44	0	0.04	4.9
10	6/28/77	7.4	2.1	140	0.80	0.4	0.1	0.4	0	-	0	0.05	5.7
	7/ 6/77	7.3	2.8	172	0.75	0.1	0.1	-	0	50	0.3	0.05	4.7
	7/13/77	-	-	-	0.40	0.2	0.1	-	0	-	0.1	0.09	5.3
	8/10/77	8.3	-	-	0.30	0.5	0.1	0.3	-	45	0	0.06	4.5
11	6/28/77	7.2	4.1	200	0.90	0	0.1	0.4	0	-	0.3	0.08	4.9
	7/ 6/77	6.2	4.1	192	0.85	0	0.1	-	0	44	0.4	0.07	5.1
	7/13/77	-	-	-	0.60	0	0.1	-	0	-	0.2	0.07	4.5
	8/10/77	8.0	-	-	0.22	0	0.1	0.2	-	51	0.4	0.08	4.6
12	6/28/77	6.7	4.2	192	0.90	0.1	0.1	0.4	0	-	0.3	0.05	4.8
	7/ 6/77	6.6	4.1	192	0.54	0	0.1	-	0	43	0.3	0.03	5.0
	7/13/77	-	-	-	0.22	0.1	0.1	-	0	-	0.1	0.38	4.5
	8/10/77	8.2	-	-	0.38	0.1	0.2	0.2	0	51	0.0	0.05	4.3
13	6/28/77	6.8	4.3	168	0.50	0	0.1	0.4	0	-	0.4	0.03	4.3
	7/ 6/77	7.2	4.8	224	0.50	0	0.1	-	0	42	0.5	0.05	4.9
	7/13/77	-	-	-	0.35	0	0.1	-	0	-	0.2	0.07	5.0
	8/10/77	-	-	-	0.15	0.1	0.1	0.2	0	51	0.3	0.06	4.3

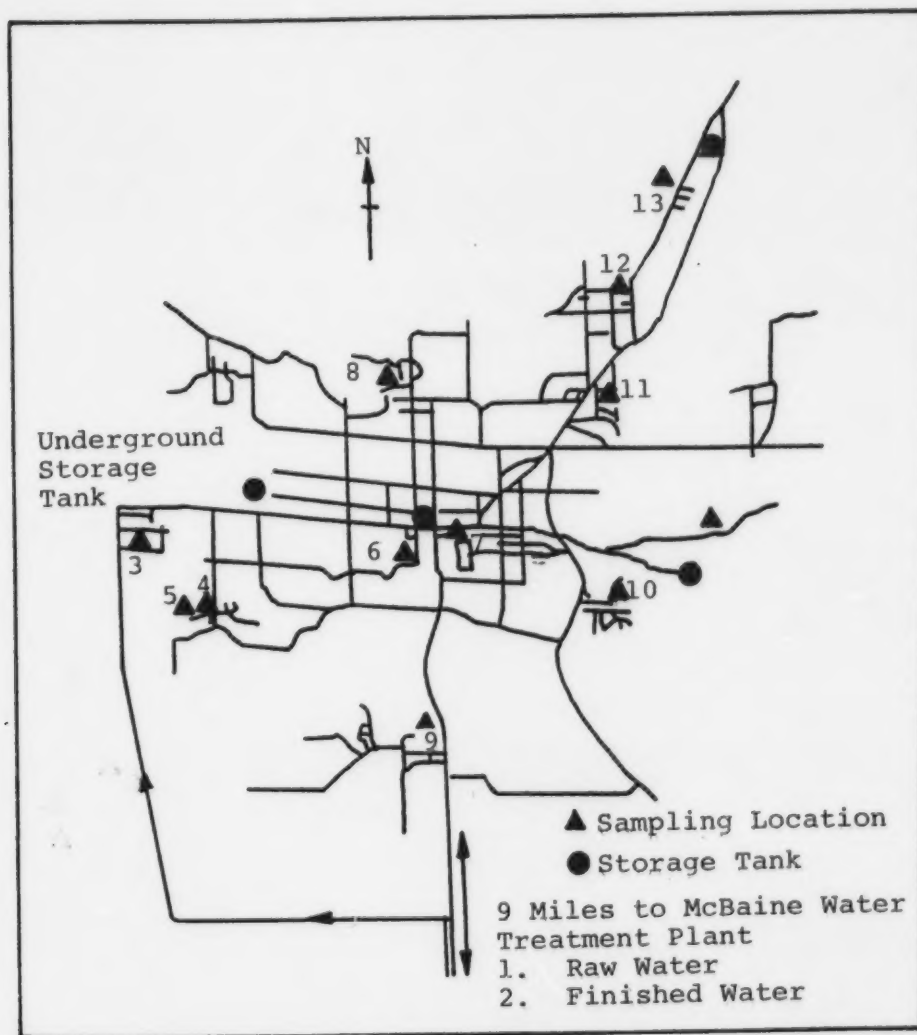


Fig. 13 Schematic of Columbia, Missouri Water Distribution System

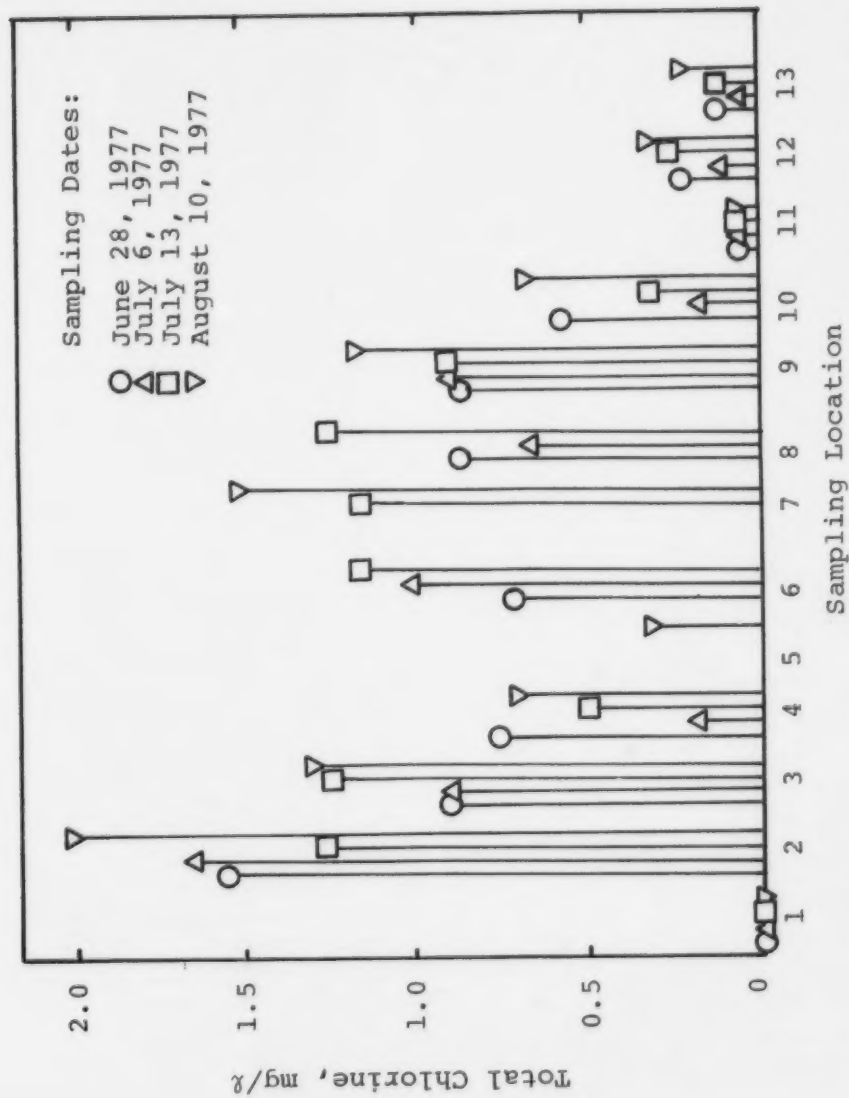


Fig. 14 Total Chlorine in Samples from the Columbia, Missouri Water Distribution System

duals was observed at two locations (Nos. 4 and 10) of the distribution system, for waters examined on July 6, 1977. Location No. 4 was on the distribution main which had high bacterial plate counts. Location No. 10 was on the distribution main which had discolored water problems.

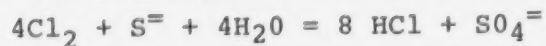
Sample locations Nos. 11 - 13 exhibited low chlorine residuals (less than 0.2 mg/l chlorine) due to the addition of untreated well water. The well water is not chlorinated before discharge into the distribution system. The water pressures of the distribution mains at the northeastern part of the city were also generally lower than the other parts of the city. The resultant low chlorine residuals at these sample locations had effected other symptoms of water quality deteriorations, such as "black water" and hydrogen sulfide odors.

Total iron concentrations in distribution water samples (Figure 15) were erratically higher than that of the finished water. The distribution pipe at sample location No. 6, where samples showed high iron concentrations, was uncoated cast iron.

The other locations with high iron concentrations were primarily those at the distant ends of the water distribution system, i.e., at sample locations Nos. 10 - 13. Both water samples at locations Nos. 10 and 11 were from dead-end mains. Red and black sediments were evident from hydrant flushings discharged from locations Nos. 10 and 11, respectively.

Due to the intermittent mixing of two different water sources at sample location Nos. 11 - 13, water qualities at these locations were expected to differ from the other parts of the Columbia water distribution system. In general, the higher values of total iron, alkalinity and hardness were observed in water samples from this area were attributed to the well water. A major difference was noted in the color of sediments discharged from the hydrant flushings. Usually hydrant flushings from sample locations at Nos. 11 - 13 were dark brown to black, while those from the remaining sample locations were red.

Dissolved sulfide was usually observed in water samples from location Nos. 10 - 13. Chen and Morris (97) reported that the reaction between dissolved oxygen and sulfide ion is slow. Thus, sulfide will coexist with oxygen in water for long periods of time, i.e., weeks. However, these investigators found that chlorine reacted with sulfide very rapidly. For a complete chemical oxidation of hydrogen sulfide to sulfate ion, theoretically, 8.5 mg of chlorine are required for every mg of hydrogen sulfide. The reaction of chlorine with sulfide may be written:



Consequently, water with chlorine residuals higher than 0.5 mg/l

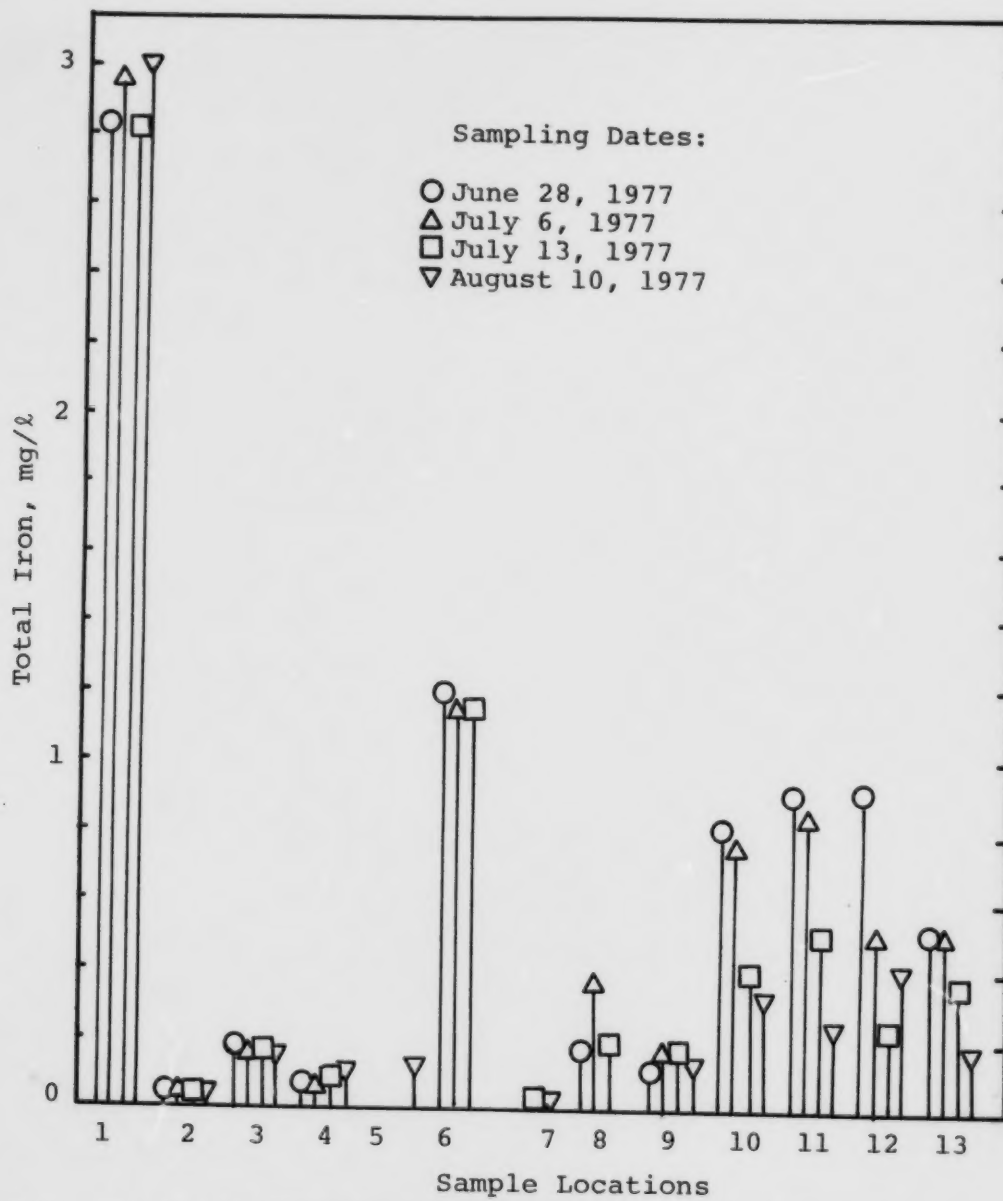


Fig. 15 Total Iron in Samples from the Columbia, Missouri, Water Distribution System

were found to be free of dissolved sulfide (Figure 16).

In Columbia most of the water mains are either cement-asbestos or cast iron. Only a small portion of the city is served by unlined cast iron pipes. Sample location No. 6 is located in one such area. Deposits of calcite and iron flocs were observed throughout the distribution mains. The corrosion of the lined cast iron pipes was not indicated.

The increase in iron in the Columbia water distribution systems may be due to iron precipitation by certain microorganisms. Organisms such as Mycobacterium, Bacillus, Pseudomonas, Arthrobacter, Enterobacter and yeasts were capable of precipitating hydrated iron oxides as their waste products. Plate counts of Columbia distribution water samples yielded heterotrophs including some iron-precipitating organisms. The results of bacterial plate counts of thirteen sampling locations at four sampling dates are shown in Figure 17. Microbial concentrations ranged from less than one organism per ml to 10^3 organisms per ml when chlorine residuals were present at concentrations of 0.05 to 2 mg/l. Over three-quarter of the water samples contained fewer than 100 organisms per ml.

Plate counts versus chlorine residuals are plotted in Figure 18. Some evidence of an inverse correlation was observed between these two parameters. The lack of chlorine residuals in portions of the Columbia distribution system is reflected in increases in bacterial plate counts, as can be seen from Samples Nos. 4, 5, 10 and 11. The predominant aerobic heterotrophs were yellow and orange-pigmented Gram negative and variable rods. Gram negative spirillum bacteria were also detected frequently.

Spore-forming bacteria and actinomycetes were detected more frequently in the areas where red water problems have been persistent. Yeasts, molds and acid-fast bacteria were also observed in water distribution samples (Table 20). Iron-precipitating, nitrogen-fixing, sulfur-transforming and stalk-producing organisms were found in most of the distribution samples examined.

When Columbia water (5 ml) was inoculated into a ferric ammonium citrate medium, a natural selection of microbial population was observed. Initially, iron-precipitating organisms precipitated iron while sulfate-reducing organisms produced hydrogen sulfide at the bottom of the culture tube. Hydrogen sulfide reacted with available iron and produced black precipitates. Upon longer incubation sulfur-precipitating organisms precipitated sulfur on the surface of ferric ammonium citrate enrichment culture liquid medium.

Stalk-producing organisms were observed frequently. These may be an important group of organisms since they can attach to

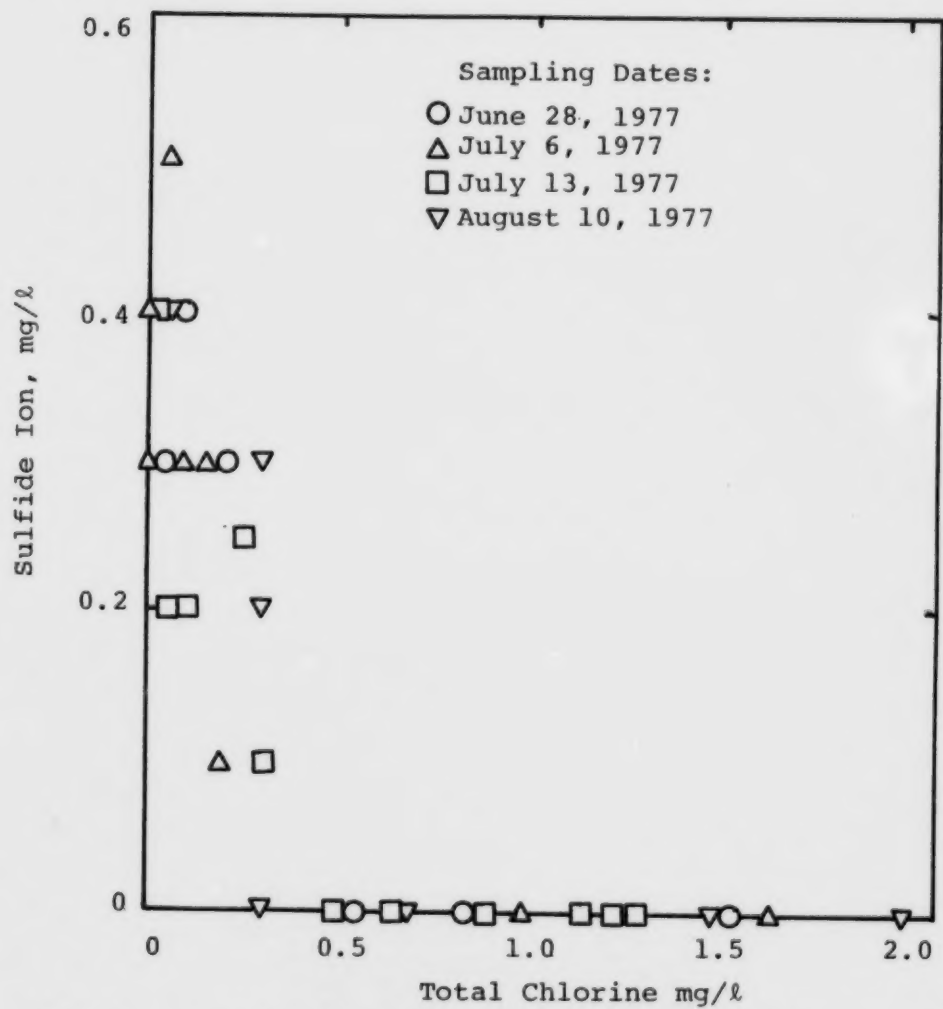


Fig. 16 Dissolved Sulfide versus Total Chlorine Residuals in Water Samples from the Columbia Water District

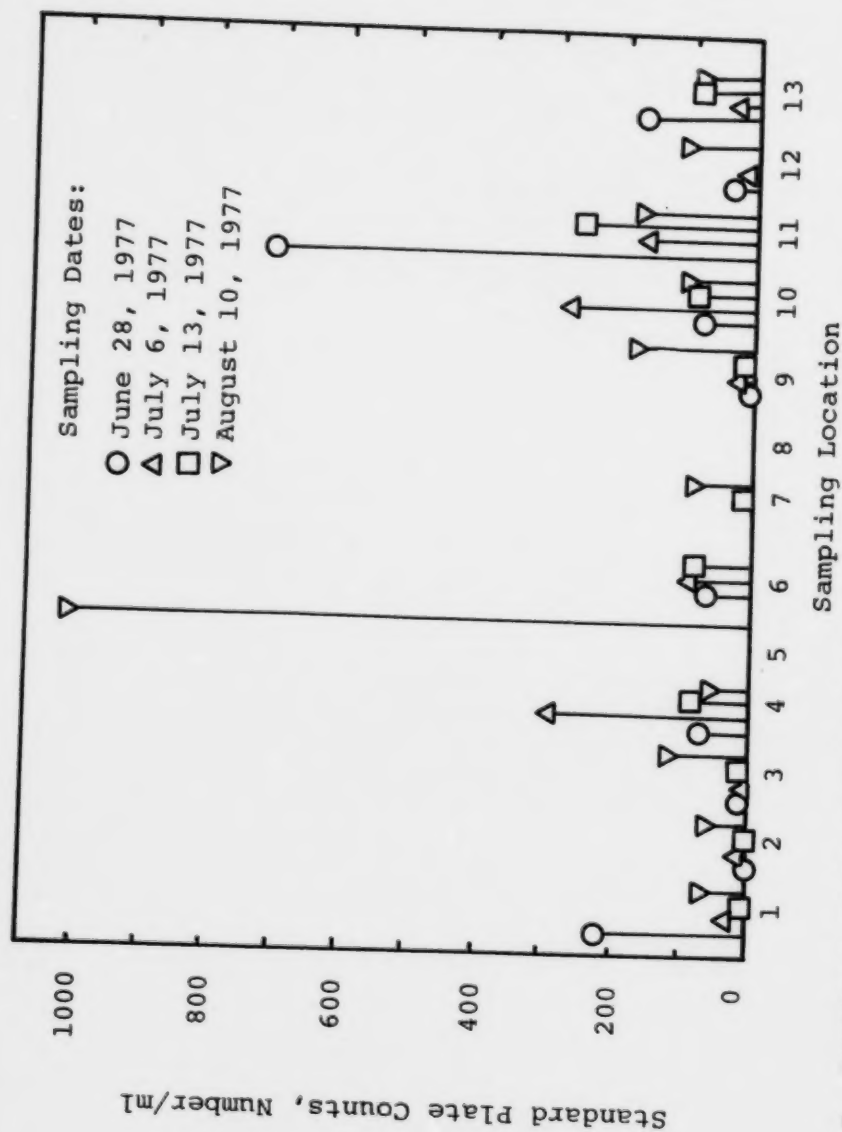


Fig. 17 Standard Plate Counts in Samples from the Columbia, Missouri, Water Distribution System

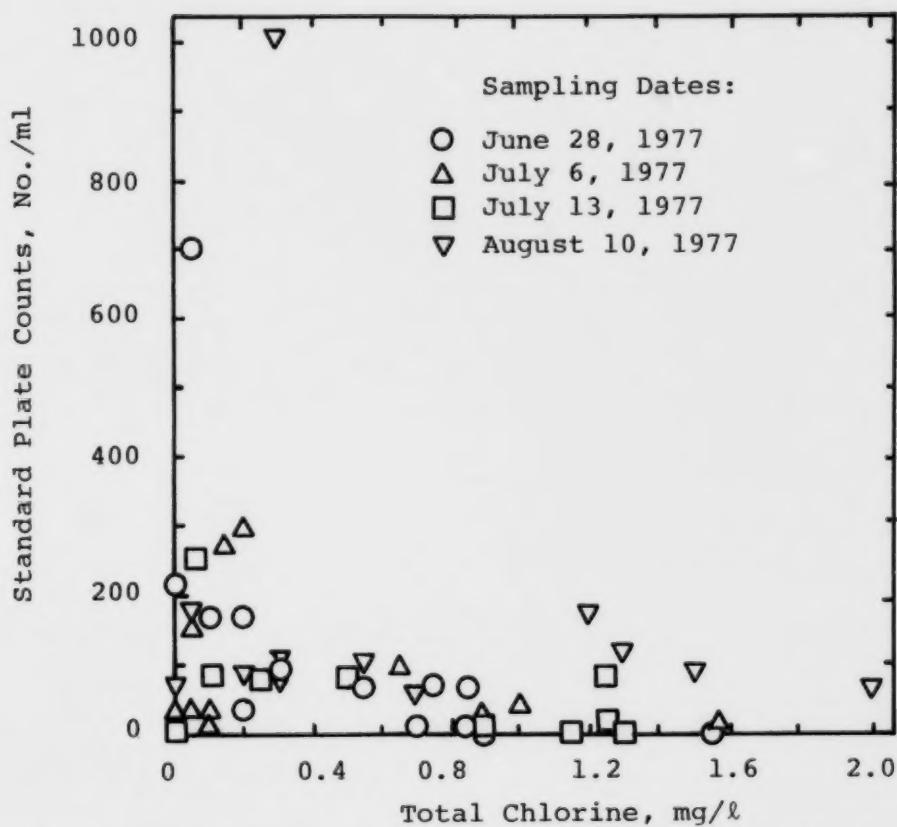


Fig. 18 Standard Plate Counts versus Chlorine Residuals in Columbia, Missouri, Water Distribution System Samples

Table 20 Compilation of Results of Microbiological Water Analysis of
Columbia Water System

Sample & Date	Modified Standard Plate Count Count/ml	Sulfate Reducers	Sulfur Oxidizers	Iron Trans- formers	N ₂ Fixers	NO ₃ Reducers	Stalk- Producing Organisms	Yeasts & Molds	Heterotrophs	Nitrifying Organisms
1) Raw water										
6/28/77	216.3	-	+	+	+	+	NM	-	+	-
7/ 6/77	30	-	+	+	+	NM	NM	-	+	+
7/13/77	7.2	+	+	+	+	+	-	-	+	NM
8/10/77	62.7	+	+	-	+	+	-	-	+	+
2) Finished water										
6/28/77	0	-	+	-	+	+	-	-	+	-
7/ 6/77	13	-	+	+	-	+	+	-	+	-
7/13/77	2.5	-	+	-	-	-	-	-	+	-
8/10/77	62.5	-	+	-	-	-	-	-	-	-
3) Rothwell										
6/28/77	6	-	-	-	+	-	-	-	+	+
7/ 6/77	2.4	-	+	+	+	-	+	-	+	-
7/13/77	15	+	+	+	+	+	+	-	+	-
8/10/77	114.5	-	-	+	-	-	-	-	+	-
4) Bray Res.										
6/28/77	70.5	-	+	+	+	+	-	-	+	-
7/ 6/77	299.5	-	-	+	+	-	-	-	+	+
7/13/77	86	-	-	+	-	+	-	-	+	-
8/10/77	56.2	-	-	+	+	-	-	-	+	-

Table 20 Compilation of Results of Microbiological Water Analysis of Columbia Water System (con't)

Sample & Date	Modified Standard Plate Count Count/ml	Sulfate Reducers	Sulfur Oxidizers	Iron Trans-formers	N ₂ Fixers	NO ₃ Reducers	Stalk-Producing Organisms	Yeasts & Molds	Heterotrophs	Nitrifying Organisms
5) Bray St. F.H. 8/10/77	TN/C	+	-	+	-	-	-	-	+	-
6) E. Parkway 6/26/77	8.6	+	-	+	-	+	-	+	+	-
7/ 6/77	41	-	+	+	-	-	-	-	+	-
7/13/77	3.6	+	+	+	+	+	-	-	+	-
7) Downtown S. 8th St. Res. 7/13/77	6.7	-	-	-	+	+	+	-	+	-
8/10/77	86.5	-	-	-	+	+	-	-	+	-
8) Proctor Dr. 6/28/77	63.2	+	+	+	+	+	+	-	+	-
7/ 6/77	96	+	-	+	+	-	-	-	+	-
7/13/77	88.5	+	+	+	+	+	-	-	+	-
9) El Cortez & Valencia F.H. 6/26/77	4	+	+	-	+	+	+	+	+	-
7/ 6/77	24	+	+	+	+	+	-	-	+	+
7/13/77	15.3	+	-	+	-	+	+	-	+	-
8/10/77	174.4	+	+	-	-	+	NM	+	+	-

Table 20 - Compilation of Results of Microbiological Water Analysis of
Columbia Water System (con't)

Sample & Date	Modified Standard Plate Count Count/ml	Sulfate Reducers	Sulfur Oxidizers	Iron Trans- formers	N ₂ Fixers	NO ₃ Reducers	Stalk- producing Organisms	Yeasts & Molds	Heterotrophs	Nitrifying Organisms
10) Bluff Blvd & Buck Run F.H.										
6/28/77	78.8	-	+	+	+	-	+	-	+	+
7/ 6/77	270	+	+	+	-	+	+	-	+	-
7/13/77	84	+	-	+	+	+	-	-	+	-
8/10/77	98.3	+	+	+	+	+	-	-	+	-
11) Calvert										
6/28/77	704	+	+	+	-	+	-	-	+	-
7/ 6/77	159	+	+	+	+	+	-	-	+	+
7/13/77	254	+	+	+	+	+	+	-	+	-
8/10/77	171.7	+	+	+	-	-	-	+	+	-
12) Pine Dr.										
6/28/77	36	+	+	+	+	+	+	-	+	-
7/ 6/77	18.3	+	+	+	+	-	-	-	+	-
7/13/77	-	+	+	+	+	+	-	-	+	-
8/10/77	101.5	+	+	+	-	-	-	+	+	-
13) Hgt redge										
6/28/77	160.4	-	+	+	+	+	+	-	+	-
7/ 6/77	28.8	-	+	+	+	+	+	-	+	+
7/13/77	80.5	+	+	+	+	-	+	-	+	-
8/10/77	84.4	-	-	+	-	-	-	+	+	-

+: Presence of Organism -: Absence of Organism
NM: Not Measured

themselves or to other organisms in establishing a biological network. Such attachment may enhance the formation of biological network. Such attachment may enhance the formation of biological accumulation on the pipe surface.

Data on organisms observed in the standard plate count versus chlorine residuals for all distribution systems studied are plotted in Figure 19. Virtually all of the distribution water samples contained fewer than 500 organisms per ml, which is the maximum plate count for potable water samples recommended by Geldreich, *et. al.* (96).

The chlorine-resistant microorganisms found in distribution systems may aid each other in promoting survival. A number of the aerobic heterotrophs have been isolated and subcultured into pure culture form for identification. Several cultures did not survive upon subculturing.

Examination of isolates using the API identification system did not yield any definitive identification. Several isolates did not grow on any media and resulted in inert reaction within the specified test period. These results indicated that commonly used subculturing media, such as the standard plate count medium, are not adequate for enumerating water distribution system organisms. An improved growth medium is necessary for identification of the isolates observed in drinking water.

From the survey of five Missouri water distribution systems, the following general observations were made.

- (1) The most frequently observed water quality changes were the loss of chlorine residuals, the decrease in dissolved oxygen concentrations and the increase in iron concentrations. Although sulfate ion concentration changes were not noticeable, increases in hydrogen sulfide were often evident.
- (2) In general, higher bacterial plate counts were observed in locations where consumers reported water quality problems. Higher plate counts were also associated with low chlorine residuals.
- (3) All five Missouri water distribution systems yielded a wide variety of microorganisms. Selective enrichment culture media yielded sulfate-reducing, sulfur-oxidizing, iron-precipitating, nitrogen-fixing, nitrifying, denitrifying, and stalk-producing organisms. These organisms belong to that group of organisms which can transform carbon, nitrogen, sulfur and iron as part of their microbiotic cycles. Water quality changes can thus be influenced and mediated by the organisms indigenous to these water distribution systems.

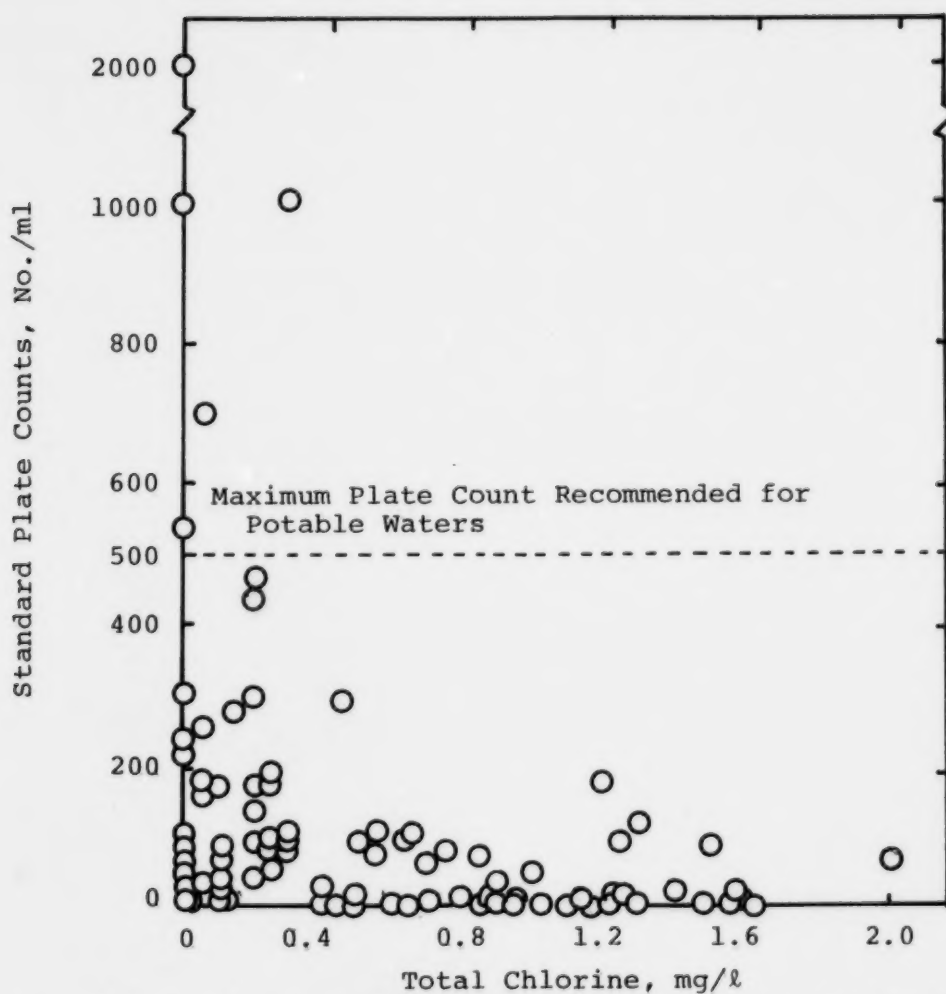


Fig. 19 Standard Plate Counts versus Chlorine Residuals for All Distribution System Water Samples Studied

NATIONAL SURVEY OF WATER DISTRIBUTION SYSTEMS

From the national questionnaire survey, several U.S. cities were selected for a more detailed water quality monitoring program. The purpose of this monitoring program was to develop base-line data concerning the water quality in the treatment plant and within a variety of distribution systems.

The cities were selected on the following basis:

- (i) geographically, to cover regions of the country
- (ii) those that had water quality problems in distribution system, and
- (iii) those that could perform water quality monitoring on a routine basis.

From the original list of 26 cities only 9 could eventually provide sufficient data that could be used to evaluate water quality changes in distribution systems. These cities were: Tacoma, Washington; Chicago, Illinois; Springfield, Illinois; Champaign, Illinois; Durham, North Carolina; Columbia, Missouri; Tampa, Florida; Minneapolis, Minnesota; and Sioux Falls, South Dakota.

Periodically, the respective water utility personnel would send the water quality data from the distribution system. The sampling of the water and chemical and microbiological analyses were performed by water utility personnel in accordance with the Standard Methods (95). In most cases, the distribution system water quality data was collected for a period of one year.

In order to determine the chemical and microbial quality of the distribution system fire hydrant flushing samples of the participating cities, sterilized sample bottles were mailed with instructions for sample collection and return. The samples were to be collected in the sterilized bottles after allowing the hydrant to flush for 60 seconds to remove stagnant water in the stem. The collected samples were analyzed soon after receipt in Columbia, Missouri. The chemical parameters analyzed were: pH, alkalinity, total iron, sulfate, sulfide, $\text{NH}_3\text{-N}$, total solids and volatile solids.

For microbiological testing, six general enrichment media were used for sulfur-oxidizing bacteria, nitrogen-fixing bacteria, nitrifying bacteria, denitrifying bacteria, sulfate-reducing bacteria, and iron-precipitating bacteria. Bacterial enumeration of various species was done by plating duplicate 1 ml and 0.1 ml samples in the above solid media except for the anaerobic

organisms (denitrifying and sulfate-reducing). Diluted Standard Plate Count (SPC) media (2-fold dilution) and R-2A media were used to enumerate the total bacterial concentration in the samples.

The following is a discussion of the results of the distribution system water quality analysis for each participating utility.

Tacoma, Washington

The major sources of water supply for Tacoma are surface reservoirs, with about 21% (on an annual basis) being supplied from ground water wells. During periods of high turbidity in the surface waters (in the spring and winter months), the well system is used to supplement the surface water supplies. Since the quality of the water from both of these sources is quite high, no clarification, softening or filtration is employed. Water is disinfected prior to pumping to the consumers. In addition, copper sulfate and powdered activated carbon are added, as needed, in the summer to individual reservoirs to control algae growth. Raw water quality data for the two sources are presented in Table 21. As expected, the finished water quality was quite similar to the raw water. Turbidity values were generally less than five turbidity units for most of the year. The free chlorine residuals leaving the surface water facility were generally between 0.6 to 0.8 mg/l as Cl. Provision is made for rechlorination is several uncovered supply reservoir outlet sites. Water quality consumer complaints are generally higher in the summer months. Table 22 summarizes the type of complaints received for the years 1976 and 1977. Most of the complaints fall under the category of "dirty water", with "taste and odor" being the second most common cause of complaint. The distribution system is 82.6% cast iron and ductile iron, 14.8% steel and asbestos cement, and 2.6% other materials. The estimated average age of the distribution system piping is about 30 years.

Water samples from 38 locations (later increased to 41) in the distribution system were collected weekly for total coliform and free chlorine residual analysis. Since May 1978, standard plate count (SPC) analysis also has been included. Tables 23 and 24 show these water quality data for May through December 1978 and January through August 1979, respectively. These data show the occurrence of high standard plate counts (> 50/ml) and the presence of total coliform at various free chlorine residual concentrations. Sample points 8, 13 and 22 are reservoir outlet samples. The rest of the sample points are located throughout the distribution system. No clear correlation between the standard plate counts and free chlorine residuals was evident. High SPC values could be observed at low as well as

TABLE 21

Raw Water Analysis - City of Tacoma, Washington

Water Characteristics	(All in mg/l except pH)		
	Green River Source		
	5/2/77	10/5/77	4/7/77
Alkalinity	18.0	13.0	74.8
Ammonia, as N	0.01	0.07	< 0.01
Calcium	4.4	4.6	18.4
CO ₂	6.0	23.1	26.9
Chloride	3.6	0.8	10.3
Hardness, mg/l as CaCO ₃ eq.	16.1	19.4	115.0
Iron	< 0.01	< 0.14	0.03
Magnesium	1.03	1.92	17.7
Manganese	< 0.01	< 0.01	< 0.01
Nitrate, as N	0.01	0.01	0.81
pH	7.2	6.9	7.0
Phosphate	< 0.01	< 0.01	< 0.1
Sulfate	0.8	1.6	16.3

TABLE 22

City of Tacoma
Water Quality Consumer Complaints

Month	Consumer Complaints						
	Dirty Water		Taste & Odors		Others		Total
	1976	1977	1976	1977	1976	1977	
January	14	10	1	1	--	--	15
February	11	8	3	3	--	1 (Soapy)	14
March	12	9	2	--	1 (Air)	--	15
April	18	15	4	--	--	1 (Air)	22
May	18	6	16	--	--	--	34
June	21	10	5	1	--	1 (Chlorine)	26
July	6	32	1	6	--	--	7
August	13	36	18	1	--	--	31
September	11	8	5	4	--	--	16
October	5	13	1	4	--	--	6
November	18	10	8	6	--	--	26
December	3	11	2	6	1 (Rocks)	--	6
Total	150	168	66	32	2	3	218
							203

TABLE 23 City of Tacoma Water Distribution System Microbiological Quality - 1978 (samples having SPC > 50/ml).

Date (Sample)	SPC (no/ml)	Free Chlorine (mg/l)	Date (Sample)	SPC (no/ml)	Free Chlorine (mg/l)
5/29 (6)	1000	0	10/30 (13)	62	0.02
5/29 (12)	130	0	11/6 (22)	(1)*	0.02
5/29 (15)	56	0	6/12 (29)	150	0.03
5/29 (26)	64	0	6/19 (16)	110	0.03
6/12 (5)	61(1)*	0	7/17 (5)	190	0.03
6/12 (8)	36(3)*	0	7/31 (24)	150	0.03
6/12 (16)	580	0	8/21 (11)	150	0.03
6/26 (15)	1700	0	8/28 (11)	1100	0.03
6/26 (19)	1700(1)*	0	9/11 (30)	60	0.03
7/3 (36)	260	0	9/18 (10)	250	0.03
7/24 (6)	140	0	12/4 (11)	3500	0.03
7/31 (26)	2300	0	5/29 (9)	320	0.04
8/14 (30)	830	0	5/29 (10)	1200	0.04
8/21 (7)	830	0	5/29 (11)	320	0.04
9/18 (37)	200	0	7/17 (6)	84	0.04
9/25 (10)	770	0	7/24 (8)	18 (4)*	0.04
10/2 (15)	97	0	8/21 (7)	830	0.04
10/16 (6)	1000	0	8/28 (21)	510	0.04
10/23 (8)	3000	0	9/11 (22)	3 (7)*	0.04
11/27 (6)	75	0	9/25 (32)	1400	0.04
7/31 (8)	45(65)*	0.01	11/27 (22)	(1)*	0.04
8/7 (12)	73	0.01	7/10 (8)	4 (3)*	0.05
8/7 (26)	830	0.01	7/10 (30)	2300	0.05
8/7 (29)	96	0.01	7/24 (23)	110	0.05
8/14 (11)	66	0.01	8/14 (32)	250	0.05
9/18 (19)	120	0.01	9/11 (6)	640	0.05
9/25 (24)	1500	0.01	9/18 (15)	380	0.05
9/25 (25)	10(5)*	0.01	9/18 (15)	66	0.05
10/2 (7)	1700	0.01	10/2 (19)	510	0.05
10/23 (22)	(1)*	0.01	10/2 (23)	120	0.05
6/26 (11)	400	0.02	10/2 (32)	1400	0.05
7/31 (11)	580	0.02	10/16 (15)	5200	0.05
8/14 (19)	86	0.02	11/13 (22)	(3)*	0.05
9/18 (11)	53	0.02	12/4 (22)	(2)*	0.05
10/9 (11)	50	0.02			
10/30 (5)	90	0.02			

TABLE 23 City of Tacoma Water Distribution System Microbiological Quality - 1978 (samples having SPC > 50/ml) - con't.

Date (Sample)	SPC (no/ml)	Free Chlorine (mg/l)	Date (Sample)	SPC (no/ml)	Free Chlorine (mg/l)
12/4 (32)	1200	0.05	8/7 (6)	100	0.16
9/4 (19)	52	0.06	7/24 (26)	150	0.17
8/28 (8)	12 (22)*	0.07	7/17 (21)	320	0.18
9/4 (8)	(2)*	0.07	7/24 (7)	150	0.18
10/23 (6)	170	0.07	8/21 (19)	110	0.18
12/11 (36)	1100	0.07	7/10 (26)	(79)*	0.19
9/18 (17)	200	0.08	7/3 (21)	900	0.2
10/2 (7)	1700	0.08	12/18 (11)	260	0.2
11/13 (7)	85	0.08	8/14 (6)	320	0.21
12/25 (29)	380	0.08	8/14 (5)	75	0.23
10/19 (12)	120	0.09	5/22 (26)	5000	0.25
11/20 (36)	7 (1)*	0.09	8/21 (37)	140	0.25
5/15 (9)	200	0.1	9/25 (4)	700	0.25
6/5 (30)	120	0.1	11/27 (15)	90	0.32
6/26 (37)	63	0.1	10/2 (4)	70	0.35
7/3 (35)	2300	0.1	10/16 (30)	380	0.38
11/20 (27)	81	0.1	8/7 (1)	(1)*	0.39
9/4 (13)	60	0.11	1/16 (3)	100	0.42
6/5 (7)	140	0.12	8/14 (33)	180	0.80
6/5 (16)	640	0.12			
6/5 (29)	94	0.12			
5/15 (10)	(1)*	0.15			
7/31 (15)	68	0.15			
8/14 (36)	300	0.15			
8/21 (27)	121	0.15			
8/21 (32)	4600	0.15			
10/2 (13)	30 (1)*	0.15			
11/20 (18)	380	0.15			

* coliform counts/100 ml

Note:

No. of samples with SPC $\geq$ 50/ml=102
 No. of samples with SPC $\geq$ 200/ml=52
 No. of samples with SPC $\geq$ 1000/ml=21
 No. samples with positive coliform
 coliform = 20

TABLE 24 City of Tacoma, Water Distribution System Microbiological Quality (Jan. - Aug. 1979) (Samples having SPC > 50 ml)

Date (Sample)	SPC (no/ml)	Chlorine Res. (mg/l)	Date (Sample)	SPC (no/ml)	Chlorine Res. (mg/l)
5/21 (36)	120	0	7/30 (4)	4000	0.02
5/14 (39)	54	0	8/6/ (7)	134	0.02
6/11 (32)	130	0	8/6 (19)	68	0.02
2/5 (39)	130	0	8/20 (17)	100	0.02
7/2 (6)	510	0	8/27 (22)	(1)*	0.02
7/2 (10)	6500	0	8/27 (39)	830	0.02
7/9 (28)	140	0	8/27 (26)	(1)*	0.02
7/9 (39)	100	0	8/27 (41)	6500	0.02
7/30 (28)	77	0	6/4 (29)	120	0.03
8/13 (5)	84	0	3/5 (41)	62	0.03
8/13 (11)	1700	0	2/19 (12)	160	0.03
8/13 (22)	(12)*	0	5/21 (41)	64	0.03
8/13 (30)	120	0	4/23 (29)	700	0.03
8/13 (29)	(1)*	0	7/30 (39)	90	0.03
8/13 (37)	71	0	7/30 (10)	97	0.03
8/13 (41)	52	0	8/6 (28)	320	0.03
8/20 (8)	(40)*	0	8/20 (16)	1200	0.03
8/20 (24)	65	0	6/25 (29)	64	0.04
8/20 (41)	6500	0	5/28 (4)	260	0.04
8/27 (27)	2900	0	4/12 (17)	210	0.04
8/27 (28)	3500	0	4/2 (11)	62	0.04
6/25 (36)	200	0.01	1/29 (40)	320	0.04
4/9 (39)	830	0.01	8/6 (4)	600	0.04
7/9 (32)	230	0.01	8/23 (28)	140	0.04
7/30 (7)	1700	0.01	8/13 (32)	57	0.04
8/13 (10)	92 (1)*	0.01	8/20 (7)	130	0.04
8/20 (19)	3500	0.01	6/11 (36)	122	0.05
8/20 (28)	80 (1)*	0.01	6/11 (20)	80	0.05
8/27 (19)	6500	0.01	3/26 (22)	2300	0.05
8/27 (32)	6500	0.01	3/26 (18)	110	0.05
6/4/ (27)	2300	0.02	5/21 (40)	64	0.05
5/7 (24)	1700 (1000)*	0.02	5/13 (41)	260	0.05
5/28 (40)	580	0.02	1/8 (6)	610	0.05
4/23 (28)	6300	0.02			
4/16 (39)	380	0.02			
4/22 (39)	510	0.02			

TABLE 24 City of Tacoma, Water Distribution System Microbiological Quality (Jan. - Aug. 1979) (Samples having SPC > 50 ml) (con't)

Date (Sample)	SPC (no/ml)	Chlorine Res. (mg/l)	Date (Sample)	SPC (no/ml)	Chlorine Res. (mg/l)
7/9 (1)	190	0.05	5/21 (15)	58	0.10
7/9 (7)	260	0.05	5/28 (27)	380	0.10
3/26 (39)	90	0.06	4/30 (39)	90	0.10
5/28 (41)	1200	0.06	4/30 (40)	57	0.10
4/30 (10)	130	0.06	4/2 (41)	100	0.10
4/9 (5)	58	0.06	8/20 (10)	260	0.10
4/2 (39)	110	0.06	8/6 (15)	150	0.10
7/2 (24)	54 (1)*	0.06	1/15 (38)	190	0.11
7/23 (6)	66	0.06	4/9 (41)	2000	0.11
6/4 (26)	61	0.07	5/28 (22)	260	0.11
5/7 (39)	52	0.07	6/11 (40)	260	0.12
2/5 (6)	2600	0.07	6/11 (8)	55	0.12
1/22 (12)	140	0.07	5/28 (26)	90	0.12
7/2 (39)	700	0.07	5/28 (18)	80	0.12
7/9 (5)	68	0.07	5/28 (13)	100	0.12
1/15 (6)	260	0.08	4/2 (28)	84	0.12
4/16 (26)	320	0.08	8/2 (6)	6500	0.12
5/28 (29)	6500	0.08	7/9 (4)	1200	0.13
6/25 (41)	72	0.08	8/20 (1)	1200	0.13
6/25 (13)	51	0.08	6/25 (29)	4000	0.14
6/4 (41)	160	0.08	8/13 (15)	380	0.15
6/4 (19)	110	0.08	6/14 (39)	200	0.17
7/30 (7)	67	0.08	6/14 (28)	2900	0.17
8/6 (23)	(1)*	0.08	6/14 (40)	770	0.18
8/20 (4)	700	0.08	5/28 (1)	6400	0.19
5/28 (29)	80	0.09	3/12 (15)	110	0.20
5/28 (39)	85	0.09	7/30 (18)	980	0.21
5/28 (2)	2300	0.09			
6/25 (39)	380	0.10			
6/25 (4)	6500	0.01			

TABLE 24 City of Tacoma, Water Distribution System Microbiological Quality (Jan. - Aug. 1979) (Samples having SPC > 50 ml) (con't)

Date (Sample)	SPC (no/ml)	Chlorine Res. (mg/l)
4/23 (38)	75	0.22
3/12 (29)	120	0.27
5/7 (25)	300	0.30
8/5 (2)	5000	0.32
2/19 (2)	210	0.34
3/19 (21)	84	0.35
6/4 (4)	80	0.38
6/11 (4)	260	0.41
5/28 (3)	50	0.44
3/12 (21)	200	0.55
1/1 (3)	640	0.56
8/6 (34)	(1)*	0.57
1/22 (31)	6500	0.60
1/29 (3)	260	0.60

* Coliform counts/100 ml

Note:

No. of samples with $SPC \geq 50/ml$ = 134

No. of samples with $SPC \geq 200/ml$ = 64

No. of samples with $SPC \geq 1000/ml$ = 30

No. of samples with positive
chloriform = 11

high chlorine residual concentrations. However, it was found that in 1978, 74 out of 102 instances of high standard plate counts ($>50/100\text{ml}$) were associated with samples having low chlorine residuals ($<0.1\text{ mg/l}$). The corresponding data for the 8 months in 1979 show that 100 out of 134 instances of high plate counts ($>50/100\text{ ml}$) were accompanied by low chlorine residuals ($<0.1\text{ mg/l}$).

In 1978, there were many instances (28 out of 102) where, despite reported free chlorine residuals greater than 0.1 mg/l (range 0.11 to 0.8 mg/l), the standard plate counts were in range 68 to 5000/ml. The 1979 data are similar with 34 out of 102 samples showing standard plate counts in the range 50 to 6500/ml even though the free chlorine residuals were greater than 0.1 mg/l (range 0.11 to 0.6 mg/l).

In 1978, total coliform were present in 20 samples. Thirteen of these were reservoir raw water samples before the application of chlorine. Only 11 samples exhibited total coliform in 1979. Three of these samples were reservoir samples prior to chlorination. Generally, a larger number of high standard plate count samples were observed in the summer months. This corresponded to some extent with high consumer complaints during these months (see Table 22).

Chicago, Illinois

The City of Chicago takes its water from Lake Michigan. The raw water is chemically treated with chlorine, fluoride, alum, polymers and occasionally, activated carbon before flocculation/coagulation and settling. Lime is added to the settled water for stabilization before it is filtered. Filtered water is further disinfected with chlorine prior to pumping into distribution systems. Water quality problems in the system are infrequent. Occasional flow variations in the distribution result in complaints of "dirty water." During late June and early July, due to seasonal proliferation of algae in Lake Michigan, slight taste and odor problems are encountered. The distribution system is 95% cast iron and about 5% ductile iron with age ranging from new to 110 years old. The average chemical water quality data for the period February 1978 to April 1979 is shown in Table 25. The chemical water quality remains practically unchanged through the distribution system indicating low chemical and biochemical activities. There is some minor fluctuation in raw water quality with the season but the overall finished water quality remains quite high throughout the year.

The results of bacterial water quality analyses in the water distribution system for 1978 are given in Table 26. Chlorine residuals remain fairly constant throughout the system.

TABLE 25 City of Chicago Average Chemical Water Quality Data for the Period Feb. 1978 Through April 1979.

Parameter	South Water District			Central & North Water Districts		
	Raw	Finished	Distribution	Raw	Finished	Cent. Dist. North Dist.
Turbidity, F.t.u.	1.5	0.2	0.2	1.0	0.18	0.2
Color, pt-co, Units	1.25	0	0	1.1	0	0
pH	8.25	8.1	8.1	8.3	8.2	8.2
Total Alkalinity, mg/l as CaCO ₃	111.0	109.0	108.0	108.0	109.0	109.0
Total Hardness, mg/l as CaCO ₃	133.0	138.0	135.0	132.0	134.0	135.0
Calcium, mg/l	37.0	38.0	37.0	36.0	37.0	37.0
Magnesium, mg/l	10.0	10.0	10.0	10.0	10.0	10.0
Sodium, mg/l	5.1	5.0	5.0	4.9	4.8	4.9
Chloride, mg/l	10.1	10.8	10.8	9.9	10.7	10.8
Sulfate, mg/l	24.1	26.5	26.6	23.4	26.0	25.8
Fluoride, mg/l	0.15	0.95	0.96	0.14	0.95	0.97
Total Phosphate, mg/l PO ₄	0.025	0.01	0.01	0.02	0.01	0.01
Dissolved Oxygen, mg/l	12.2	12.4	11.8	12.2	12.4	12.0
Total Residue, mg/l	174.0	170.0	170.0	167.0	168.0	170.0
Ammonia, mg/l as N	0.01	0.01	0.01	0.01	0.01	0.01
Nitrate-Nitrate, mg/l as N	0.26	0.25	0.24	0.26	0.24	0.25
Total Iron, mg/l	0.04	0.01	0.01	0.03	0.01	0.01

TABLE 26

City of Chicago Water Distribution System

SUMMARY OF BACTERIAL ANALYSES

1978

STATION	PUMPING STATION DISCHARGE			DISTRIBUTION SYSTEM WATER			
	NUMBER OF SAMPLES	AVERAGE BACTERIA 35°-48 HR. PER ml.	AVERAGE COLIFORM PER 100 ml. MF	NUMBER OF SAMPLES	mg/l Cl ₂ RESIDUAL AT SAMPLE POINT	AVERAGE BACTERIA 35°-48 HR. PER ml.	AVERAGE COLIFORM ORGANISMS PER 100 ml. MF
MAYFAIR	642	0	0.000	709	0.35	0	0.386
JEFFERSON	283	0	0.000	306	0.40	0	0.006
LAKEVIEW	333	19	0.000	402	0.46	0	0.030
SPRINGFIELD	603	2	0.007	610	0.43	1	0.216
CENTRAL PARK	606	0	0.000	606	0.47	0	0.074
CHICAGO AVENUE	293	0	0.000	544	0.45	1	0.080
CERMAK	305	0	0.000	591	0.42	1	0.194
NORTH & CENTRAL WATER DISTRICTS	3065	3	0.002	3768	0.43	1	0.165
68th STREET	594	0	0.000	795	0.65	0	0.008
WESTERN AVENUE	418	0	0.000	720	0.47	0	0.168
ROSELAND	721	0	0.000	607	0.45	0	0.000
SOUTHWEST	576	0	0.000	528	0.50	7	0.008
SOUTH WATER DISTRICT	2309	0	0.000	2650	0.48	2	0.050
TOTAL CHICAGO SYSTEM	5374	3	0.000	6418	0.45	1	0.118

The average coliform concentration was always less than one per 100 ml and the SPC was quite low ($\leq 7/\text{ml}$). In summary, the water quality in the distribution system in Chicago, Illinois was found to be excellent.

Springfield, Illinois

Springfield, Illinois takes its water from Lake Springfield. The raw water, after initial screening, is pumped to the treatment plant where it is first chlorinated. Thereafter, ferrous sulfate, polymers, lime, activated carbon and ammonia are added prior to its clarification in Spaulding precipitators. The clarified water is filtered through dual media filters. Carbon dioxide is added to the filter influent as well as fluoride. The treated water is then pumped to the distribution system. In the spring and fall, powdered activated carbon doses are higher in order to control taste and odor-producing compounds. In the winter months, the feed rates for ferrous sulfate and polymers are higher to aid clarification.

The primary water quality complaints are related to taste and odor during the spring and fall periods as a result of lake turnover. During the summer, a much less frequent complaint rate is generally related to "red water." These complaints originate in a portion of the system that has unlined cast-iron pipes.

The distribution system pipe types and ages are, as follows: about 50% of the system is cement-lined cast-iron pipe of less than 30 years age; about 30% of the system is unlined cast-iron between 30 to 110 years old; about 15% of the system is cement-lined ductile iron pipe of less than 20 years of age; the remaining 5% consists of reinforced concrete pipe approximately 10 years old, a small area of cement asbestos pipe of approximately 35 years of age and a short section of steel tarcoated pipe about 45 years of age.

Water quality data for the distribution system for the period November 1978 through March 1980 are provided in Table 27. The water quality in the distribution system during this period was quite good. A decrease in the chlorine residuals was observed as the treated water travelled through the distribution system.

However, free chlorine residuals persisted throughout the system with the result that coliform counts were absent in all but two samples (Sample Point No. 2 & 3, 11/6/79). SPC values were also remarkably low throughout the system due to the presence of free chlorine residuals. Alkalinity and hardness values were relatively constant. Iron and dissolved oxygen measurements were not made on the samples. These parameters would have helped

TABLE 27 Springfield, Illinois Water Quality Changes in Distribution System

Sample Point No.	Date	pH	Hardness (mg/l as CaCO ₃)	Total Alkalinity (mg/l as CaCO ₃)	Chlorine Res. Free (mg/l)	Chlorine Res. Total (mg/l)	Total Coliform	SPC (no/ml)
Finished Water	11/5/78	9.7	111	15-45	0.7	1.4	0	5+3 sp (0.1ml)
	12/12/78	9.9	106	21-47	0.8	1.4	0	0
	12/19/78	9.8	106	16-43	0.8	1.6	0	-
	1/9/79	9.1	110	31	0.3	1.4	0	0
	2/20/79	9.2	109	32	0.0	1.2	1/200 ml	0
	3/13/79	9.6	103	33	0.6	1.6	0/200 ml	2 + sp
	4/17/79	9.4	107	40	0.0	2.0	0/200 ml	0/200 ml
	5/22/79	9.2	130	48	-	2.0	0	0
	6/5/79	9.6	122	45	0.1	1.4	0/200 ml	2 + sp
	7/17/79	9.6	110	37	0.1	1.2	0/200 ml	2
	8/7/79	9.6	106	34	0.1	1.2	0/200 ml	2 sp
	9/18/79	9.1	99	37	0	1.2	0/200 ml	1+1 sp
	10/9/79	9.2	100	40	0	1.5	0/200 ml	3+2 sp
	11/6/79	9.3	104	40	0	1.4	0/200 ml	2+1 sp
	12/4/79	9.9	015	41	0.1	1.1	0/200 ml	2+1 sp
	1/15/80	9.4	117	44	0.1	1.1	0/200 ml	1+1 sp
	2/5/80	10.0	120	43	0.03	1.0	0/200 ml	4
	3/18/80	10.1	114	37	0.8	1.0	0/200 ml	1

TABLE 27 Springfield, Illinois Water Quality Changes in Distribution System (con't)

Sample Point No.	Date	pH	Hardness (mg/l as CaCO ₃)	Total Alkalinity (mg/l as CaCO ₃)	Chlorine Res. Free (mg/l)	Chlorine Res. Total (mg/l)	Total Coliform	SPC (no/ml)
1	11/5/78	9.5	111	46	0.5	1.0	0	1 sp
	12/12/78	9.4	100	44	0.8	1.2	0	1
	12/19/78	9.7	108	42	0.7	1.1	0	-
	1/9/79	9.3	116	47	0.3	1.0	0/200 ml	2
	2/20/79	9.2	130	48	0.8	1.0	0	0
	3/13/79	9.2	100	38	0.7	1.0	0/200 ml	-
	4/17/79	9.2	100	38	0.5	1.1	0/200 ml	5+2 sp
	5/22/79	8.9	101	31	0.5	1.2	0/200 ml	0
	6/5/79	9.4	110	29	0.3	1.0	0	0
	7/17/79	9.6	106	35	0.5	1.0	0/200 ml	-
	8/7/79	9.1	102	33	-	1.0	20/100 ml	2+1 sp
	9/18/79	9.1	98	36	0.3	0.9	0/200 ml	0
	10/9/79	-	101	38	0.3	1.0	0/200 ml	2+2 sp
	11/6/79	8.9	108	40	0.3	1.0	0/200 ml	2+1 sp
	12/4/79	9.6	105	42	0.5	1.0	0/200 ml	2+1 sp
	1/15/80	9.3	107	44	0.4	1.1	-	-
	2/5/80	10.0	107	37	0.4	1.1	0/200 ml	9
	3/18/80	9.8	108	33	0.5	1.3	0/200 ml	1
2	11/5/78	9.3	114	45	0.6	0.9	0	1
	12/12/78	9.3	106	46	0.3	1.0	1/200 ml	1+ sp
	12/19/78	9.7	107	41	0.6	0.9	0	-

TABLE 27 Springfield, Illinois Water Quality Changes in Distribution System (con't)

Sample Point No.	Date	pH	Hardness (mg/l as CaCO ₃)	Total Alkalinity (mg/l as CaCO ₃)	Chlorine Res. Free (mg/l)	Chlorine Res. Total (mg/l)	Total Coliform	SPC (no/ml)
2 (con't)	1/9/79	9.4	114	45	0.7	1.1	0/200 ml	1+2 sp
	2/20/79	9.1	134	47	0.6	0.9	0	0
	3/13/79	9.3	103	38	0.6	1.0	0/200 ml	-
	4/17/79	9.4	105	35	0.4	1.0	0/200 ml	1+ sp
	5/22/79	8.9	012	30	0.3	1.0	0/200 ml	0
	6/5/79	9.4	106	29	0.3	0.9	0	0
	7/17/79	9.5	111	37	0.6	1.1	0/200 ml	-
	8/7/79	9.3	97	34	-	1.0	0/200 ml	0
	9/18/79	9.0	99	36	0.5	1.1	0/200 ml	2
	10/9/79	9.0	99	38	0.2	0.9	0/200 ml	2+1 sp
	11/6/79	8.9	101	40	0.3	1.0	10/200 ml	3
	12/4/79	9.5	108	42	0.6	1.1	0/200 ml	1+1 sp
	1/15/80	9.5	104	41	0.4	1.1	0	-
3	2/5/80	10.0	105	36	0.5	1.1	0/200 ml	0
	3/18	10.0	108	32	0.4	1.1	0/200 ml	1
	11/5/78	9.3	115	45	0.4	0.8	0	1+sp
	12/12/78	9.6	105	44	0.7	0.7	0	2
	12/19/78	9.7	111	45	0.5	1.0	0	-
	1/9/79	9.4	112	46	0.6	1.0	0/200 ml	2
	2/20/79	9.1	133	48	0.7	1.0	0	0
	3/13/79	9.3	105	38	0.8	1.1	0/200 ml	-

TABLE 27 Springfield, Illinois Water Quality Changes in Distribution System (con't)

Sample Point No.	Date	pH	Hardness (mg/l as CaCO ₃)	Total Alkalinity (mg/l as CaCO ₃)	Chlorine Res. Free (mg/l)	Total (mg/l)	Total Coliform	SPC (no/ml)
3 (con't)	4/17/79	9.5	106	37	0.6	1.1	0/200 ml	2+sp
	5/22/79	8.9	100	30	0.4	0.9	0/200 ml	1
	6/5/79	9.5	111	30	0.4	1.2	0	0
	7/17/79	9.6	110	37	0.4	0.9	0/200 ml	-
	8/7/79	9.4	98	35	-	1.0	0/200 ml	1+1 sp
	9/18/89	9.0	96	35	0.5	1.0	0/200 ml	1
	10/9/79	9.0	101	38	0.3	1.0	0/200 ml	3+1 sp
	11/6/79	9.0	103	41	0.4	1.1	23/200 ml	1+1 sp
	12/4/79	9.6	105	41	0.5	1.0	0/200 ml	2+1 sp
	1/15/80	9.4	106	39	0.5	1.1	-	-
	2/5/80	10.1	104	36	0.6	1.2	0/200 ml	2
	3/18/80	10.1	108	33	0.4	1.2	0/200 ml	1
Raw Water	11/5/78	9.3	180	0-131	0	0	3/10 ml	13+1sp(0.1ml)
	12/12/78	8.3	188	0-132	0	0	3/10 ml	17+ sp
	12/19/78	8.3	180	0-134	0	0	3/10 ml	-
	1/9/79	8.2	206	132	-	-	1/10 ml	15+sp/0.1 ml
	2/20/79	8.1	220	141	0	0	7/10 ml	23/0.1 ml
	3/13/79	7.9	175	118	-	-	0/10 ml	2/200 ml
	4/17/79	8.2	147	90	-	-	13/10 ml	200/0.1ml+sp
	5/22/79	7.8	150	84	-	-	16/10 ml	17/0.1 ml+sp
	6/5/79	8.0	169	92	-	-	0/10 ml	23/0.1 ml+sp

TABLE 27 Springfield, Illinois Water Quality Changes in Distribution System (con't)

Point No.	Date	pH	Hardness (mg/l as CaCO ₃)	Total Alkalinity (mg/l as CaCO ₃)	Chlorine Res. Free (mg/l)	Total (mg/l)	Total Coliform	SPC (no/ml)
Raw Water	7/17/79	7.9	191	118	0	0	12	-
	8/7/79	8.0	192	107	0	0	18/10 ml	10+2 sp
	9/18/79	7.8	167	108	0	0	90/10 ml	100+50sp/0.1m
	10/9/79	7.9	171	119	0	0	42/10 ml	1sp/0.1 ml
	11/6/79	8.0	174	123	-	-	3/10 ml	9+2 sp/0.1
	12/4/79	8.3	181	122	-	-	2/10 ml	-
	1/15/80	8.3	187	136	0	0	2/10 ml	2/0.1 ml
	2/5/80	8.2	195	140	0	0	0/10 ml	120
	3/18/80	8.1	211	138	0	0	0/10 ml	40

Abbreviation: sp. = spreading colonies

in assessing water quality changes.

Champaign, Illinois

Groundwater is the source of water supply for Champaign, Illinois. It is obtained from 18 wells located in the Teays River Valley. The raw water is lime softened, coagulated with ferric sulfate, stabilized with sulfuric acid, disinfected with chlorine and filtered prior to distribution.

The treatment process remains unchanged throughout the year except for chlorine feed. Between April and November breakpoint chlorination is practiced on an alternate-month basis in order to minimize "bad water" complaints. A free chlorine residual between 1.0 - 1.5 mg/l is maintained in the treated water during this period. During winter months a combined chlorine residual of about 2.0 mg/l is maintained in the treated water. The presence of naturally-occurring ammonium ion in the raw water requires no ammonia addition for combined chlorine treatment.

The water distribution system dates back to 1884. However, due to system renovations, over 50% is less than 20 years old. Over 93% of the distribution main is cast or ductile iron, about 6% galvanized iron or wrought iron and very small section asbestos cement pipe.

Consumer complaints associated with the water quality in Champaign fall into the following three categories:

- i. "Bad Water" - Generally in dead-end areas of the system. The water is described as grey to blackish in color and associated with a rotten-egg taste and odor.
- ii. "Chlorine Taste" - These complaints are experienced when breakpoint chlorination is practiced at the plant. This complaint is more appropriately classified as "a change in taste" because of the change in chlorination practice.
- iii. "Miscellaneous Complaints" - These are complaints associated with customers plumbing system, hot water heater deterioration, etc.

Table 28 lists the typical consumer complaints for the period of January through July 1979.

The typical raw and treated water analysis is shown on Table 29. Table 30 shows the water quality data in the distribution system for the period January through July 1979. The

TABLE 28
 Consumer Complaints - January - July, 1979
 Northern Illinois Water Corporation
 Champaign, Illinois

Month	Consumer Complaint			Total
	"Bad Water"	"Chlorine Taste"	Misc.	
Jan	2	0	0	2
Feb	1	0	1	2
Mar	5	0	2	7
Apr	3	6	4	13
May	4	0	2	6
Jun	6	2	3	11
Jul	14	1	2	17

TABLE 29

Typical Raw & Treated Water Analysis
at Champaign, Illinois

Parameter	Raw Water	Treated Water
Iron, mg/l	1.1	<0.02
Manganese, mg/l	0	-
Calcium (as CaCO ₃), mg/l	136	30-35
Magnesium (as CaCO ₃), mg/l	116	45-50
Ammonia, mg/l	1.0	<2.0
Sodium, mg/l	26	<40.0
Silica, mg/	0.3	-
Flouride, mg/l	0.3	0.9 - 1.2
Chloride, mg/l	0	<5.0
Sulfate, mg/l	0.2	<40.0
Nitrate, mg/l	0.3	<2.0
Total Alkalinity, mg/l (as CaCO ₃)	312	100 - 120
Hardeness, mg/l (as CaCO ₃)	252	75 - 85
Total Dissolved Solids, mg/l	303.0	<180
pH, units	7.8	8.8 - 9.0
odor, units	0	0
Turbidity units	3	<0.1
color, units	5	0

TABLE 30
Water Quality Evaluations of Champaign, Illinois Water Distribution System (Northern Illinois Water Corp.)

Sample Point	Date 1979	pH	Water Quality Parameters										SPC no/ml	Coliform M.F. no/ml	Non-Coliform no/ml
			Total Alkalinity mg/l as CaCO ₃	Hardness mg/l as CaCO ₃	Chlorine Residuals		Fluoride mg/l	Temp OF							
					Free mg/l	Total mg/l									
Stand-pipe	1/3	8.9	107	80	0.00	1.80	1.01	45							
	1/5	8.7	112	81	0.00	2.00	0.98	46							
	1/10	8.8	117	82	0.00	1.74	0.97	45							
	1/11	8.7	115	78	0.00	1.78	0.93	48							
	1/16	8.8	108	83	0.00	1.90	0.92	47							
	1/18	8.9	114	80	0.00	2.06	0.96	48							
	1/23	8.8	109	82	0.00	2.00	0.97	49							
	1/26	8.7	107	81	0.00	2.00	0.98	48							
	1/30	8.7	108	81	0.00	1.90	1.01	47							
	2/1	8.7	110	82	0.00	1.90	1.01	47							
	2/6	8.7	108	83	0.00	1.92	0.93	49							
	2/8	8.8	111	82	0.00	1.80	0.98	48							
	2/14	8.9	110	81	0.00	2.04	0.93	50							
	2/15	8.9	112	82	0.00	2.10	0.90	49							
	2/20	9.0	111	81	0.00	1.96	0.91	48							
2/22	9.0	109	83	0.00	1.90	0.93	47								
2/27	8.9	111	79	0.00	1.86	1.02	49								
3/1	8.9	113	83	0.00	1.98	1.05	48								
3/6	8.9	114	84	0.00	1.92	0.93	48								
3/8	9.0	114	86	0.00	1.96	0.92	52			0	0	0			
3/13	9.0	109	78	0.00	1.90	0.95	49			0	0	0			
3/15	9.1	104	82	0.00	1.80	1.00	49			0	0	0			
3/20	9.0	124	77	0.00	1.81	0.99	45			0	0	0			
3/22	9.0	119	82	0.00	1.82	0.96	48								
3/27	8.8	109	83	0.00	2.10	1.04	49			11	0	0			
3/28	8.8	116	77	-	-	0.99	51								
4/3	8.9	114	82	0.42	-	1.07	53								
4/5	8.9	106	80	0.00	-	1.07	53				0	0	0		
4/10	8.7	114	86	0.00	-	1.08	53			0	0	0	0		
4/12	8.7	117	83	0.00	-	1.08	56				1	0	0		
4/17	8.9	109	80	0.55	-	1.01	55				0	0	0		
4/19	8.8	113	82	0.62	-	0.97	56			0	0	0	0		
4/24	8.9	115	82	0.42	-	0.97	57				2	21	0		
4/26	9.0	114	79	0.54	-	0.97	57				0	0	0		

TABLE 30
Water Quality Evaluations of Champaign, Illinois Water Distribution System (Northern Illinois Water Corp.) (con't)

Sample Point	Date 1979	pH	Total Alkalinity mg/l as CaCO ₃	Hardness mg/l CaCO ₃	Water Quality Parameters						
					Chlorine Residuals Free mg/l	Total mg/l	Fluoride mg/l	Temp. °F	SPC no/ml	Coliform M.F. no/ml	Non- Coliform no/ml
Stand-pipe	5/1	8.8	120	81	0.98		0.97	57		0	0
	5/3	8.7	118	83	0.98		0.92	58		0	0
	5/8	9.0	117	75	0.00	1.60	1.02	62	0	0	0
	5/10	9.0	115	76	0.00	1.96	0.99	64		0	0
	5/15	8.8	120	78	0.00	1.90	1.04	62		0	0
	5/17	8.7	122	78	0.00	1.80	1.00	61		0	0
	22	8.9	117	77	0.00	1.90	0.98	60	0	0	0
	5/24	8.9	119	80	0.00	1.72	1.05	61		0	0
	5/29	8.7	115	83	0.00	2.02	0.94	62		0	0
	5/31	8.9	119	80	0.00	2.00	1.00	62		0	0
	6/5	8.9	115	79	0.00	2.00	1.00	64		0	0
	6/7	8.7	117	81	0.00	2.30	1.02	62		0	0
	6/12	8.8	109	86	0.88		0.99	58		0	0
	6/14	8.9	110	82	0.50		1.07	61		0	0
Bond-ville Elevated Tank	6/19	9.9	110	82	0.70		0.97	68		0	0
	6/21	8.8	108	83	1.23		1.02	68		0	0
	6/28	8.8	115	81	0.00	1.96	1.00	60		0	0
	7/3	8.7	112	81		1.86	1.05	66		0	0
	7/6	8.6	113	83		1.70	1.07	63		0	0
	7/10	8.5	123	84		1.80	1.00	63		0	0
	7/12	8.8	112	81		1.80	1.03	64		0	0
	7/17	8.7	111	78		1.83	1.04	64	0	0	0
	7/19	-	117	80			1.00	64		0	0
	7/24	8.8	118	78		1.80	0.99	64	0	0	0
	7/26	8.7	112	79		1.70	1.01	66		0	0
	7/31	9.0	115	81			1.06	66		0	2
	1/3	9.1	123	81		1.22	0.90	47			
	1/5	8.8	114	80		1.00	0.92	49			
1/10	8.7	135	87		0.70	1.00	46				
1/11	8.7	131	83		1.20	0.93	42				
1/16	8.9	114	82		1.00	0.91	42				
1/18	8.7	124	83		1.10	0.94	43				
1/23	9.0	116	84		1.82	0.95	46				
1/26	8.9	119	79		1.30	0.99	40				
1/30	8.5	113	87		0.18	1.04	43				

TABLE 30
Water Quality Evaluations of Champaign, Illinois Water Distribution System (Northern Illinois Water Corp.) (con't)

Sample Point	Date 1979	pH	Water Quality Parameters									
			Total Alkalinity mg/l as CaCO ₃	Hard- ness mg/l CaCO ₃	Chlorine Free mg/l	Residuals Total mg/l	Fluoride mg/l	Temp °F	SPC no/ml	Coliform M.F. no/ml	Non- Coliform no/ml	
Bond- ville Elevated Tank	2/1	8.5	122	86		1.66	0.96	40				
	2/6	8.5	118	84		1.52	1.07	42				
	2/8	8.6	103	84		1.40	1.00	41				
	2/14	8.8	118	84		0.90	0.99	40				
	2/15	8.7	117	84		0.96	0.92	40				
	2/20	9.0	117	82		1.24	0.90	40				
	2/22	9.0	119	82		1.00	0.92	40				
	2/27	9.0	105	87		1.00	0.98	39				
	3/1	8.7	119	83	0.00	0.90	1.03	40				
	3/6	9.0	116	84	0.00	0.20	0.98	42		0	0	
	3/8	9.2	121	80	0.00	1.50	0.87	44		0	0	
	3/13	9.2	131	90	0.00	1.40	0.99	44		0	0	
	3/15	9.1	128	86	0.00	0.20	1.03	42		0	0	
	3/20	9.1	132	78	0.00	0.94	1.00	43		0	0	
	3/22	9.0	131	83	0.00	1.40	0.98	44	21	0	0	
	3/27	9.0	126	79	0.00	0.82	1.10	45				
	3/28	8.9	118	81	0.00	-	1.00	47				
	4/3	9.0	134	83		1.20	1.10	50		0	1	
	4/5	8.9	120	80		1.30	1.07	44		0	0	
	4/10	8.9	121	82		0.0	1.09	46	1	0	0	
	4/12	8.7	125	83		0.0	1.12	56		20	0	
	4/17	8.8	126	81		0.49	1.04	47	1	0	0	
	4/19	8.9	126	79		0.0	0.86	48		0	0	
	4/24	9.0	126	81		0.20	0.99	48		0	0	
	4/26	9.0	128	85		0.04	0.99	48		0	0	
	5/1	9.1	122	77	0.03		0.98	54		0	0	
	5/3	8.8	128	84		0.12	0.90	-		0	0	
	5/8	8.7	130	82		0.26	0.97	58	0	0	0	
	5/10	8.6	123	82		0.06	0.99	60		0	0	
	5/15	8.9	121	74		1.30	1.00	61		0	0	
	5/17	8.8	123	78		1.72	1.01	59	8	0	0	
	5/22	8.8	112	78		1.80	0.99	61		0	0	
	5/24	8.8	122	80		1.18	1.09	62		0	0	
	5/29	8.9	133	81		1.50	0.88	62		0	0	
	5/31	8.8	119	79		1.00	0.93	62		0	0	

TABLE 30
Water Quality Evaluations of Champaign, Illinois Water Distribution System (Northern Illinois Water Corp.) (con't)

Sample Point	Date 1979	Water Quality Parameters									
		Total Alkalinity mg/l as CaCO ₃	Hardness mg/l CaCO ₃	Chlorine Residuals Free mg/l	Total mg/l	Fluoride mg/l	Temp. °F	SPC no/ml	Coliform M.F. no/ml	Non-Coliform no/ml	
Bondville Elevated Tank	6/5	9.0	120	80	1.10	0.99	66		0	0	
	6/7	9.0	126	80	1.40	0.98	65		0	0	
	6/12	8.8	119	85	0.20	1.00	64		0	0	
	6/14	8.6	120	83	0.21	1.10	64		0	0	
	6/19	9.0	128	75	0.10	0.95	64		0	0	
	6/21	9.0	120	80	0.50	1.03	64		0	0	
	6/26	9.0	129	82	0.18	1.04	65		0	0	
	6/28	8.6	121	83	1.20	1.08	64		0	0	
	7/3	8.7	115	78	0.90	1.10	72		1	0	
	7/6	8.7	127	81	0.90	1.07	69		0	0	
	7/10	8.6	125	81	0.72	0.97	70		0	0	
	7/12	8.6	123	83	0.50	1.04	70		0	0	
	7/17	8.9	114	78	0.78	1.06	70	0	0	0	
	7/19	8.5	118	77	-	1.08	72		0	0	
	7/24	8.5	125	83	0.06	1.05	72	4			
7/26	8.8	127	80	0.20	1.02	72					
7/30	-	-	-	-	-	-	42	-	-		
7/31	8.7	128	86	1.10	-	1.10	70	0	0		

Standpipe sampling site is midway between the treatment plant and the extremity of the distribution system. The Bondville sampling site is located at an extremity of the distribution system. The water quality in the distribution system is excellent. There is some decrease in chlorine residuals as the water travels from the plant to the extremity of the distribution system. Except for few days in April there was sufficient total chlorine residual in the system. The bacteriological quality of the water was generally very good except for two days in April and one day in July when confirmed coliform counts were observed in the samples. The Standpipe samples showing positive coliform had, in one instance, zero chlorine residual (April 12) and 0.42 mg/l free residual in the second sample (April 24). The Bondville sample had a positive coliform on April 12 and also had no chlorine residual, while the sample on July 3 which showed a positive coliform had about 0.9 mg/l total chlorine residual. There was no definite relationship between the presence of coliforms and the absence of chlorine residuals, at least in these five samples. In a few samples non-coliform colonies were observed on membrane filter plates. These non-coliform colonies were not present when chlorine residuals were low or zero. The standard plate counts were generally quite low (<42 /ml) throughout the system. The samples at the extremity of the system had high SPC as compared to the Standpipe samples.

Total hardness remained relatively constant throughout the system during the sample period. Alkalinity values increased slightly as the water travelled to the distribution system extremities.

In summary, the water quality of the Champaign, Illinois water distribution system was quite good. The poor bacteriological quality (high SPC and coliform counts) did not correlate well with low chlorine residuals. However, in two incidents of high coliform counts, the chlorine residuals were zero. The limited water quality data on the distribution system did not provide reasons for customer complaints. Iron, dissolved oxygen and sulfide measurements of the water could have helped to evaluate the water quality problems. Sulfate ion measurements may be of particular importance in Champaign since the addition of sulfuric acid for pH reduction provides virtually all the sulfate ion. The introduction of sulfate ion during treatment may therefore stimulate the activity of sulfate-reducing bacteria.

Durham, North Carolina

Durham, N.C. obtains raw water from a lake source. It

has had a history of consumer complaints with regard to quality of water in the distribution system. The complaints are generally among consumers living near the dead end lines or areas of low flow in the distribution system. The consumer complaints generally consist of: red water problems, odor of rotten eggs, and disagreeable tastes. The city has performed several previous studies to determine the water quality changes in the distribution systems. The results of these studies indicate a strong correlation between high total plate counts, low or no chlorine residuals, dissolved oxygen depletion and water quality problems.

The city has six different sampling points for determining the water quality changes in the distribution system. The pertinent water quality data from these sampling points are given in Table 31. The standard plate counts were measured after 2 day and 4 day incubation periods. The data in Table 31 indicate that sample point No. 1, which was farthest from the water treatment plant, consistently showed no chlorine residuals, low dissolved oxygen, and high standard plate counts. The quality at this sample point was generally poor. This sample point represents a relatively large dead-end main recently installed with few customers. The total iron concentration was generally lowest of all the sample points. Despite the adverse water quality indication at Sample Point No. 1, there were no known consumer complaints in the area. It was indicated by the Durham officials that during early 1978 there were complaints in this area. They eliminated the complaints by bleeding water continuously through a 3/4 inch line at a flow rate of 5 to 10 gpm.

Sample point No. 2 was also quite far from the water treatment plant and exhibited poor water quality. This sample point is on a recently installed large lined ductile iron main serving relatively few customers. Chlorine residuals were often zero with high total iron and standard plate count values. There were two instances (10/28/78 and 7/27/79) when total coliform was found in the samples from this location. In one instance, on 7/27/79, there was no chlorine residual which could have accounted for the presence of the coliforms. However, in the second case, on 10/28/78, the total chlorine residual was 0.5 mg/l. Dissolved oxygen levels were higher at sample point No. 2 than at sample point No. 1, but there was a definite decrease in dissolved oxygen as compared with the water treatment plant finished water.

Sample Point No. 3 was located in a dead end main connected to relatively old pipes. Generally, some residual

TABLE 31 Water Quality Evaluations of Water Distribution System in Durham, NC

Sample Point	Date	Water Quality Parameters											
		D.O. (mg/l)	pH	Chlorine Residual		Iron Dis.	Total	Hardness (mg/l as CaCO ₃)	Alkalinity (mg/l as CaCO ₃)	Total Coliform (no/100 ml)	SPC at 35°C		Total Phosphate (mg/l as P)
				Free	Total						2 day (no/ml)	4 day (no/ml)	
1	10/3/78	4.3	7.5	0	0	0.12	0.17	20	29	-	3000	8000	--
	10/28/78	1.0	8.9	0	0	0.08	0.41	28	36	0	*	*	0.60
	11/20/78	1.3	8.9	0	0	0.05	0.54	62	33	0	1100	900	0.95
	12/21/78	1.1	8.7	0	0	0.05	0.37	32	33	0	230	TNTC	0.55
	1/23/79	1.6	7.9	0	0	0.06	0.43	26	23	0	0	69	0.70
	3/9/79	10.9	7.2	0	0	0.06	0.44	18	11	0	400	1170	0.50
	3/28/79	9.4	7.3	0	0	0.10	2.53	18	14	0	940	>10,000	0.90
	5/31/79	1.6	8.2	0	0	<0.05	1.20	22	24	0	21	-	0.50
	7/21/79	0.9	7.9	0	0	<0.05	24	25	0	0	>500	>500	0.8
	8/23/79	1.1	8.1	0	0	<0.05	26	31	0	0	>500	>500	0.20
2	10/3/78	5.1	7.4	0	0	0.10	1.10	24	30	-	480	1260	--
	10/28/78	7.3	7.4	0	0.5	0.24	0.24	26	25	1	*	*	0.60
	11/22/78	6.9	7.3	0	0.3	0.05	0.40	22	26	0	16	110	0.80
	12/21/78	8.6	7.4	0.4	0.5	0.05	0.45	26	22	0	0	0	0.60
	1/23/79	10.5	7.2	0.5	0.6	0.06	0.58	24	13	0	0	13	1.00
	3/9/79	10.9	6.9	0.8	0.8	<0.05	0.68	16	9	0	0	2	1.20
	3/28/79	9.9	7.0	0.8	0.9	<0.05	1.12	18	13	0	0	7	0.70
	5/31/79	7.0	7.3	0.6	0.7	0.06	2.30	24	20	0	0	-	0.70
	7/21/79	4.8	7.2	0	0	<0.05	0.97	26	20	1	58	150	0.90
	8/23/79	4.3	7.3	0	0.2	<0.05	1.10	24	28	0	15	23	0.40

TABLE 31 Water Quality Evaluations of Water Distribution System in Durham, NC (con't)

Sample Point	Date	D.O. (mg/l)	pH	Water Quality Parameters										Total Phosphate (mg/l as P)
				Chlorine Residual		Iron Dis.	Total	Hardness (CaCO ₃)	Alkalinity (mg/l as CaCO ₃)	Total Coliform (no/100 ml)	SPC at 35°C			
				Free	Total						2 day (no/ml)	4 day (no/ml)		
3	10/3/78	5.9	7.4	Trace	Trace	0.34	3.30	20	31	-	5300	5700	--	
	10/28/78	7.6	7.5	1.4	1.8	0.13	3.70	22	23	0	*	*	1.90	
	11/22/78	7.1	7.1	0.6	0.8	0.10	8.10	24	27	0	0	4	1.70	
	12/21/78	9.0	7.4	0.6	0.9	0.10	6.40	28	22	0	3	5	1.15	
	1/23/79	10.9	7.3	0.8	1.0	0.09	7.00	22	13	0	7	10	2.10	
4	3/9/79	10.7	6.9	0.7	0.9	<0.05	6.86	16	9	0	6	7	2.20	
	3/28/79	9.6	7.0	0.7	0.9	0.11	4.30	20	13	0	30	25	0.90	
	5/31/79	7.1	7.3	0.6	0.7	0.06	7.70	24	18	0	13	-	1.90	
	7/27/79	4.9	7.2	0.1	0.2	<0.05	5.80	24	25	0	52	90	1.70	
	8/23/79	4.2	7.3	0.3	0.4	<0.05	7.00	24	29	0	130	130	1.10	
	10/3/78	5.6	9.3	0.1	0.3	0.1	5.80	32	42	0	6900	3000	--	
	10/28/78	7.8	8.7	1.0	1.4	0.38	7.30	36	37	0	*	*	1.50	
	11/22/78	6.9	8.4	0.3	0.5	0.06	9.00	28	26	0	0	0	1.20	
12/21/78	8.7	8.2	0.6	0.7	0.10	7.90	26	25	0	0	10	0.90		
	1/23/79	10.6	7.9	0.8	0.8	0.12	5.80	28	16	0	0	0	1.40	
	3/9/79	10.4	7.5	0.8	0.9	<0.05	5.23	18	13	0	0	0	2.10	
	3/28/79	9.4	7.4	0.6	0.8	0.06	5.45	20	16	0	0	3	1.00	
	5/31/79	6.9	7.2	0.5	0.6	0.06	5.30	24	24	0	0	-	1.00	
	7/27/79	5.0	7.6	0	0.1	<0.05	5.20	28	30	0	0	spr	1.30	
8/23/79	3.9	7.9	0	0.3	<0.05	1.50	30	30	0	0	13	0.40		

TABLE 31 Water Quality Evaluations of Water Distribution System in Durham, NC (con't)

Sample Point	Water Quality Parameters													Total Phosphate (mg/l as P)
	Date	D.O. (mg/l)	pH	Chlorine Residual		Iron Dis.	Total	Hardness (mg/l as CaCO ₃)	Alkalinity (mg/l as CaCO ₃)	Total Coliform (no/100 ml)	SPC at 35°C		4 day (no/ml)	
				Free	Total						2 day (no/ml)	3 day (no/ml)		
5	10/3/78	7.1	7.5	1.9	2.3	0.09	0.27	22	27	-	0	0	10	--
	10/28/78	8.5	7.3	2.0	2.7	0.11	0.58	24	24	0	*	*	*	0.60
	11/22/78	8.4	7.1	1.3	1.5	0.05	0.27	24	25	0	0	0	0	1.70
	12/21/78	9.5	7.4	1.6	1.9	0.05	0.20	28	22	0	0	0	1	0.60
	1/23/79	11.2	7.1	1.8	2.1	0.05	0.48	24	12	0	spr	spr	spr	1.00
6	3/9/79	10.5	6.8	0.9	1.1	<0.05	0.29	12	10	0	0	0	0	1.10
	3/28/79	9.5	6.7	1.5	1.7	<0.05	0.80	16	11	0	0	0	2	0.50
	5/31/79	5.7	6.6	0.7	0.7	<0.05	1.00	24	17	0	0	0	-	0.70
	7/27/79	5.8	7.0	0.8	0.8	<0.05	0.39	24	23	0	0	0	0	1.00
	8/23/79	4.9	7.4	1.3	1.5	<0.05	0.73	24	26	0	0	0	0	0.40
Raw Water	3/9/79	11.0	6.9	1.7	1.9	<0.05	3.65	16	11	0	0	0	0	3.00
	3/28/79	9.7	6.8	0.8	0.9	<0.05	3.64	16	12	0	0	0	2	1.30
	5/31/79	7.0	7.2	2.0	2.0	<0.05	4.00	22	19	0	0	0	-	1.30
	7/27/79	5.4	7.3	0.2	0.4	<0.05	4.60	26	27	0	0	0	7	3.00
	8/23/79	4.6	7.3	0.5	0.7	<0.05	2.80	24	30	0	1	1	35	0.70
Raw Water	10/3/78	6.3	6.8	0	0	-	-	20	24	2000	spr	spr	-	--
	10/23/78	6.5	6.8	-	-	-	-	20	23	2150	*	*	*	0.03
	11/22/78	-	7.1	-	-	-	-	20	20	660	spr	spr	spr	--
	12/21/78	8.4	6.7	-	-	-	-	18	16	380	spr	spr	-	--
	1/23/79	10.9	6.8	0	0	-	-	18	16	2000	spr	spr	-	0.15
Raw Water	3/9/79	9.9	6.4	0	0	-	2.45	12	8	40	spr	spr	spr	--
	3/28/79	9.2	6.6	0	0	-	4.30	14	10	353	spr	spr	-	--
	5/31/79	7.3	6.8	0	0	-	0.015	20	17	0	33	-	-	--
	7/27/79	5.3	6.7	0	0	-	1.40	22	22	0	390	-	-	--
	8/23/79	5.5	6.8	0	-	-	1.70	22	21	0	spr	spr	-	--

TABLE 3.31 Water Quality Evaluations of Water Distribution System in Durham, NC (con't)

Sample Point	Water Quality Parameters												
	Date	D.O. (mg/l)	pH	Chlorine Residual		Iron Dis.	Hard- linity		Alka- linity (mg/l as CaCO ₃)	Total Coliform (no/100 ml)	SPC at 35°C		Total Phosphate (mg/l as P)
				Free	Total		Total	(mg/l as CaCO ₃)			2 day (no/ml)	4 day (no/ml)	
Fin- ished Water	10/3/78	7.7	7.5	3.1	3.3	-	-	20	26	0	0	-	--
	10/28/78	8.6	7.2	3.0	3.1	-	-	20	23	0	*	*	0.35
	11/22/78	-	6.6	1.7	1.9	-	-	20	25	0	0	4	0.36
	12/21/78	9.2	7.4	1.4	1.6	-	-	20	21	0	0	11	0.31
	1/23/78	11.6	7.2	1.7	1.9	-	-	20	25	0	0	-	0.55
	3/9/79	11.2	7.0	1.5	1.7	-	0.015	12	9	0	0	-	0.22
	3/28/79	9.9	7.0	1.5	1.7	-	-	14	12	0	0	-	0.18
	5/31/79	7.7	7.1	1.5	1.6	-	-	20	18	0	0	-	--
	7/21/79	6.1	7.1	1.5	1.8	-	0.015	22	26	0	0	-	0.08
	8/23/79	4.6	7.1	2.5	2.7	-	0.006	22	27	0	0	-	0.22

Abbreviations: Spr=Spreading Colonies; TNTC=Too numerous to count; *=Plates contaminated

chlorine was present at this location resulting in a lower bacterial count. There was an observed decrease in chlorine residuals compared to the finished water. At certain times, e.g., 10/3/78, trace chlorine residuals were associated with high standard plate counts ($>5000/\text{ml}$). Total iron concentrations ranged from 3.3 to 8.1 mg/l, which was much higher than the values observed at sample points Nos. 1 and 2. Dissolved iron concentrations ranged from 0.05 to 0.34 mg/l. It was apparent that the increase in total iron concentration in these samples was due to corrosion of mains. The City is using Calgon C-9, a liquid zinc-orthophosphate product, at a dosage of 1 mg/l to control the corrosion problem. A depletion in dissolved oxygen of 0.2 to 1.8 mg/l was observed as compared with the finished water leaving the treatment plant.

Sample point No. 4 was close to the treatment plant but represented a section having heavily tuberculated mains with a history of "red water" and other complaints. The cleaning and lining of the mains in this area has reduced the complaints considerably. However, total iron concentrations were quite high (between 1.5 to 9.0 mg/l) which indicated that the "red water" problems may not have been cleared. The higher chlorine residuals present in the water samples resulted in low bacterial counts except in one sample (10/3/78) where the standard plate counts were 6900/ml despite a total chlorine residual of 0.3 mg/l and a free chlorine residual of 0.1 mg/l. The magnitude of D.O. drop observed in sample point No. 3 was also observed at this location.

Sample Point No. 5 was also located relatively close to the treatment plant in an area with no reported water quality problems. The water quality at this location was quite similar to the finished water. Chlorine residuals were high, standard plate counts were quite low, often zero, even after 4 days incubation. Dissolved oxygen concentrations were quite high between 7.1 and 11.2 mg/l. Dissolved and total iron levels were lowest of all the sample points, but the total iron concentrations were higher than the corresponding finished water values. This increase of total iron concentration appears to be due to corrosion of the distribution system.

Sample point No. 6 was located near sample point No. 4. This sample point represents a low-flow area which has a history of "red water" and other complaints. This sample point is similar to sample point No. 4 except that no main cleaning or lining has been practiced. Since this sample point was included late in the study with the result that

only six months data was available for this location. The water quality at this point is quite similar to that at sample point No. 4. Chlorine residuals remained high. SPC values were low and total coliforms absent. Iron was present as particulate (or suspended) matter with practically no dissolved iron. Dissolved oxygen concentrations were quite high throughout the sample period. The prolonged incubation period (4 days) for SPC generally produced higher counts. In many instances, where 2 days of incubation indicated zero counts, four days of incubation produced some colonies.

In addition to the chemical analysis data presented in Table 31 the City of Durham, N.C. provided data on additional parameters, such as, sulfide, sulfate, ammonia-N, nitrate-N and total phosphates. In this respect, Durham conducted a most comprehensive distribution system evaluation. Sulfides were absent in all samples. The raw water had low sulfate levels of about 5 mg/l, which increased after treatment to about 18-24 mg/l. Sulfate levels did not change in the distribution system.

Ammonia-N concentrations in the distribution system were generally less than 0.18 mg/l, while $\text{NO}_3\text{-N}$ levels varied from 0.43 to 0.88 mg/l. These low levels of $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ may have little significance.

Total phosphate concentrations of the treated water was about 0.18-0.22 mg/l. A maximum of 3 mg/l P (sample 6, 3/9/79) was found in the distribution system. The higher level of phosphates in the distribution system was due to the addition of zinc-orthophosphate (Calgon-9) for corrosion control.

In summary, the "red water" water quality problems at Durham, N.C. appear to be due to corrosion of the mains in many parts of the distribution system as indicated by high values of total iron. The absence or low levels of chlorine residuals in water samples (sample point No. 1 & 3), resulted in high values of SPC and, occasionally, the presence of total coliforms. There was a definite depletion in dissolved oxygen as the water moved to more distant point in the distribution system. This may have been due to the chemical oxidation of iron and microbial respiration or both.

Columbia, Missouri

The Columbia, Missouri water source is ground water. The intake wells are located at McBaine, Missouri, 15 km south of Columbia, in the Missouri River alluvium. Water

is aerated, lime softened, filtered and disinfected before pumping. In the city, a chlorine booster solution provides additional disinfection. There are some deep wells in the city which are used to supplement the water supply in case of high demands. These well waters are not treated prior to pumping to the distribution systems. The type of distribution water quality problems encountered include cloudiness, and "red water". The city samples on a biweekly basis at six sampling points throughout the distribution system in addition to raw and finished water samplings. Table 32 shows the water quality data in the distribution system for the period September 1978 to August 1979.

The incubation periods used for SPC in this instance were 2 days and 6 days.

Sample point No. 1, located in the west part of the city was supplied by 15 cm (6 inch) diameter lined cast iron main installed less than 10 years ago. Sufficient chlorine residuals (free and total) were maintained at this site during most of the period. However, three times during this period chlorine residuals dropped to zero at this location (11/1/78, 6/6/79 and 8/28/79). Each time, the SPC values increased. High SPC values ($>50/\text{ml}$) were also observed when free chlorine residuals were as high as 1.6 mg/l (2/14/79). Total coliform counts were always lower than 1 per 100 ml even in samples having zero chlorine residuals. In several instances, the membrane filter coliform plates upon incubation produced unidentified pink or red colonies. These colonies were evident in samples regardless of chlorine residual concentrations. The significance of these atypical coliform colonies was not determined.

Sample point No. 2 is located in the southwestern part of the town on a 15 cm (6 inch) diameter cement lined cast iron main about 15 years old. Total and free chlorine residuals were maintained at this site for most of the study period. Despite the high chlorine residuals, this location had the highest SPC values. Low chlorine residual did not necessarily result in the highest bacteria counts. Although total coliforms were always less than one per 100 ml, many of these coliform membrane filter plates showed large numbers of pink or red colonies.

Sample point No. 3 is located at a fire station in the east edge of the town. The water is supplied by a 30 year old 30 cm (12 inch) diameter asbestos cement pipe. While the chlorine residuals at this site were lower than at sample points 1 and 2, they were generally adequate. The SPC values were also low, except on 8/28/79 when the SPC was 323/ml.

TABLE 3.32 Water Quality Evaluations of Water Distribution System in Columbia MO

Sample Point	Water Quality Parameters											Average SPC at 35°C	
	pH	Alka- linity (mg/l as CaCO ₃)	Hard- ness (mg/l as CaCO ₃)	Chlorine		Iron (mg/l)	D.O. (mg/l)	Coliform MF (no/100 ml)	Average SPC at 35°C				
				Free (mg/l)	Total (mg/l)				(no/ml) 2 days	(no/ml) 6 days			
1	9/6/78	8.26	134	150	4.0	4.2	0.063	-	<1	4	1		
	9/20/78	8.49	122	144	3.3	3.45	0.01	-	<1	1	3		
	10/4/78	8.90	136	142	1.0	1.1	0.015	-	<1	29	66		
	11/1/78	8.61	154	150	0	0	0.019	-	<1*	88	86		
	11/22/78	9.0	148	150	0.7	0.75	0.05	-	<1	3	18		
	12/6/78	8.26	142	150	0.95	1.0	0.031	-	<1	8	11		
	12/19/78	8.99	144	150	1.11	1.3	0.047	-	<1	6	5		
	1/10/79	8.87	128	-	1.00	1.10	0.014	11.0	<1	3	4		
	1/13/79	8.48	168	168	1.20	1.30	0.018	10.8	<1	-	-		
	2/14/79	9.65	150	140	1.60	1.60	0.024	10.8	<1*	62	78		
	2/28/79	8.74	150	154	1.50	1.70	0.034	11.4	<1	48	63		
	3/14/79	9.02	128	152	1.35	1.55	0.018	10.2	<1	0	0		
	4/4/79	8.91	126	146	1.92	2.02	0.012	10.4	<1	1	1		
	4/18/79	8.98	134	142	1.02	1.15	0.016	9.4	<1	0	0		
	5/9/79	8.41	120	152	1.80	1.95	0.024	9.2	<1	9	-		
	5/23/79	8.65	138	152	1.75	1.92	0.012	9.2	<1	26	-		
	6/6/79	8.77	136	192	0	0	0.026	9.0	<1	50	-		
	6/20/79	8.38	134	184	0.45	0.60	0.01	8.7	<1	7	8		
	7/4/79	8.61	130	130	0.36	0.42	0.01	8.6	<1	58	-		
	7/16/79	8.68	146	140	0.30	0.30	0.01	8.1	<1	3	-		
	7/31/79	8.77	144	142	0.28	0.49	0.021	8.6	<1	55	-		
	8/13/79	8.58	134	144	0.20	0.20	0.021	8.1	<1*	282	-		
	8/28/79	8.69	134	142	0	0	0.015	7.5	<1	54	-		

*Unidentified pink-red colonies on MF plates

TABLE 32 Water Quality Evaluations of Water Distribution System in Columbia MO (con't)

Sample Point	Date	pH	Water Quality Parameters									
			Alkalinity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Chlorine Residuals		Total (mg/l)	Iron (mg/l)	D.O. (mg/l)	Coliform MF (no/100 ml)	Average SPC at 35°C (no/ml)	
					Free (mg/l)						2 days	6 days
2	9/6/78	8.39	138	144	3.8		3.8	0.057	-	<1*	4	9
	9/20/78	8.67	118	140	3.45		3.6	0.014	-	<1*	7	9
	10/4/78	8.99	158	150	0.9		1.15	0.023	-	<1*	217	246
	11/1/78	8.73	160	150	0.5		0.6	0.019	-	<1*	47	52
	11/22/78	8.98	160	148	1.3		1.35	0.095	-	<1*	26	24
	12/6/78	8.39	142	148	0.92		1.0	0.004	-	<1*	69	51
	12/19/78	8.95	140	150	1.45		1.56	0.012	10.0	<1*	48	53
	1/10/79	9.03	126	-	0.75		0.85	0.01	11.1	<1*	40	50
	1/31/79	8.95	130	138	1.55		1.65	0.022	10.8	<1*	-	-
	2/14/79	9.19	146	162	1.70		1.75	0.024	11.2	<1*	7	10
	2/28/79	8.96	144	152	1.80		1.90	0.018	11.3	<1*	61	63
	3/14/79	8.96	122	152	1.45		1.55	0.012	10.2	<1*	82	92
	4/4/79	8.94	122	148	2.12		2.22	0.014	10.4	<1*	91	91
	4/18/79	9.29	110	140	4.05		4.15	0.002	9.6	<1*	108	116
	5/9/79	9.39	132	160	1.95		2.10	0.026	9.0	<1*	51	-
	5/23/79	9.81	120	144	2.60		2.72	0	9.2	<1*	47	-
	6/6/79	9.66	130	202	0.15		0.15	0.026	8.8	<1*	31	34
	6/20/79	9.35	142	164	0.31		0.50	0.004	8.8	<1*	154	176
	7/4/79	9.56	112	150	0.30		0.30	0.006	8.7	<1*	49	-
	7/16/79	9.74	152	138	0.25		0.25	0	8.2	<1*	32	-
	7/31/79	8.57	138	154	0.45		0.50	0.021	8.8	<1*	160	-
	8/13/79	8.56	142	154	0.10		0.15	0.021	8.0	<1*	400	-
	8/28/79	8.90	138	146	0.00		0.00	0.014	7.6	<1*	62	-

*Unidentified pink-red colonies on MF plates

TABLE 32 Water Quality Evaluations of Water Distribution System in Columbia MO (con't)

Sample Point	Date	Water Quality Parameters									
		pH	Alkalinity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Chlorine Residuals		Total (mg/l)	Iron (mg/l)	D.O. (mg/l)	Coliform MF (no/100 ml)	Average SPC at 35°C (no/ml)
					Free (mg/l)						
3	9/6/78	8.37	174	170	2.5		2.5	0.048	-	<1	0
	9/20/78	8.27	192	195	2.0		2.1	0.006	-	<1	0
	10/4/78	8.39	215	200	1.1		1.2	0.017	-	<1*	8
	11/1/78	8.29	232	218	0.3		0.5	0.017	-	<1*	9
	11/22/78	8.30	238	240	0.6		0.65	0.016	-	<1	13
	12/6/78	8.15	210	208	0.35		0.36	0	-	<1	3
	12/19/78	8.36	230	242	0.1		0.1	0.014	-	<1	4
	1/10/79	8.68	202	-	0.4		0.45	0.018	10.3	<1*	0
	1/31/79	8.44	224	212	0.6		0.63	0.012	10.1	<1	11
	2/14/79	8.69	240	214	0.5		0.5	0.006	0	<1*	-
	2/28/79	8.40	220	222	0.3		0.4	0.01	10.3	<1*	5
	3/14/79	8.51	210	206	0.65		0.75	0.016	10.4	<1	8
	4/4/79	8.19	256	234	0.20		0.22	0.01	10.2	<1	1
	4/18/79	8.21	252	234	0.40		0.45	0.006	9.5	<1*	4
	5/9/79	8.19	236	224	0.42		0.50	0.014	9.3	<1	1
	5/23/79	8.62	142	164	1.40		1.42	0.096	9.2	<1	5
	6/6/79	8.86	134	184	0.2		0.2	0.014	9.2	<1*	-
	6/20/79	8.36	150	200	0.44		0.50	0.018	9.1	<1	-
	7/4/79	8.71	130	160	0.25		0.30	0.012	8.5	<1	52
	7/16/79	8.65	140	160	0.11		0.15	0	8.4	<1	1
	7/31/79	8.68	140	148	0.05		0.10	0.021	8.2	<1	-
	8/13/79	8.56	144	154	0.05		0.10	0	8.2	<1*	9
	8/28/79	8.64	156	162	0		0	0.015	7.9	<1*	78
											323

*Unidentified pink-red colonies on MF plates

TABLE 32 Water Quality Evaluations of Water Distribution System in Columbia MO (con't)

Sample Point	Water Quality Parameters												Average SPC — at 35°C (no./ml) 2 days 6 days	
	pH	Alka- linity (mg/l as CaCO ₃)	Hard- ness (mg/l as CaCO ₃)	Chlorine		Iron (mg/l)	D.O. (mg/l)	Coliform MF (no./100 ml)						
				Free (mg/l)	Total (mg/l)									
4	9/6/78	8.57	210	198	2.6	2.6	0.003	-	<1	1	0			
	9/20/78	8.29	190	194	2.05	2.10	0.014	-	<1	0	4			
	10/4/78	8.33	218	210	2.45	0.55	0.015	-	<1*	1	20			
	11/1/78	8.13	274	248	0.40	0.50	0.018	-	<1	1	2			
	11/22/78	8.30	268	264	0.18	0.20	0.017	-	<1	18	-			
	12/6/78	8.18	240	222	0.25	0.25	0	-	<1	1	1			
	12/19/78	8.29	276	242	0.2	0.2	0.016	-	<1	1	2			
	1/10/79	8.78	204	-	0.45	0.47	0.002	10.6	<1	0	0			
	1/31/79	8.47	238	222	0.55	0.55	0.008	10.3	<1	-	-			
	2/11/79	9.02	164	152	1.75	1.80	0.92	0	<1*	92	88			
	2/28/79	8.47	220	224	0.76	0.85	0.014	10.9	<1	0	1			
	3/14/79	8.45	206	208	0.80	0.85	0.012	10.1	<1	1	8			
	4/4/79	8.20	258	240	0.2	0.2	0.008	10.2	<1	4	5			
	4/18/79	8.66	184	194	2.65	2.75	0	9.6	<1	1	2			
	5/19/79	8.13	250	238	0.40	0.42	0.004	9.2	<1	16	-			
	5/23/79	8.73	130	166	2.10	2.25	0.01	9.2	<1	3	-			
	6/6/79	8.58	126	180	0.10	0.15	0.047	9.0	<1	29	42			
	6/20/79	8.36	138	178	0.60	0.60	0.01	8.9	<1	64	71			
	7/4/79	8.63	128	160	0.30	0.30	0	8.7	<1	50	-			
	7/16/79	8.63	132	144	0.25	0.30	0	8.2	<1	38	-			
	7/31/79	8.52	136	158	0.21	0.30	0.021	8.1	<1	22	-			
	8/13/79	-	-	-	0.10	0.15	-	-	<1	0	-			
	8/28/79	8.70	150	150	0	0	0	7.8	<1	9	-			

*Unidentified pink-red colonies on MF plates

*Unidentified pink-red colonies on MF plates

TABLE .32 Water Quality Evaluations of Water Distribution System in Columbia MO (con't)

Sample Point	Water Quality Parameters											
	pH	Alkalinity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Chlorine Residuals		Iron (mg/l)	D.O. (mg/l)	Coliform MF (no/100 ml)	Average SPC			
				Free (mg/l)	Total (mg/l)				at 35°C (no/ml)	2 days	5 days	
5	9/6/78	8.53	150	154	4.0	4.1	0.001	-	<1	2	1	
	9/20/78	8.45	136	164	4.1	4.2	0.027	-	<1	3	1	
	10/4/78	8.92	140	152	1.15	1.2	0.027	-	<1	3	5	
	11/1/78	8.73	152	150	0.65	0.7	0.018	-	<1*	80	64	
	11/22/78	8.73	172	150	1.2	1.25	0.07	-	<1	5	-	
	12/6/78	8.54	144	148	0.8	0.92	0.019	-	<1	3	3	
	12/19/78	8.69	144	156	1.1	1.22	0.042	-	<1	1	3	
	1/10/79	9.11	128	-	0.8	0.87	0.004	11.0	<1	2	32	
	1/31/79	8.98	134	142	1.65	1.72	0.037	10.7	<1	-	-	
	2/14/79	8.48	240	230	0.4	0.4	0.014	-	<1	1	1	
	2/28/79	8.96	142	154	1.5	1.6	0.026	10.7	<1*	9	9	
	3/14/79	8.82	132	158	1.4	1.5	0.02	10.4	<1	3	38	
	4/4/79	8.91	120	146	2.35	2.45	0.026	10.5	<1	3	8	
	4/18/79	9.11	122	150	2.7	1.75	0.014	9.6	<1	3	36	
	5/19/79	8.44	122	156	2.12	2.22	0.108	8.8	<1	8	-	
	5/23/79	8.69	136	144	2.5	2.5	0.016	9.0	<1	0	-	
	6/6/79	8.41	132	194	0	0	0.014	8.8	<1	0	5	
	6/20/79	8.37	138	166	0.60	0.65	0.31	8.8	<1	7	23	
	7/4/79	-	-	-	-	-	-	-	-	-	-	
	7/16/79	8.53	124	154	0.60	0.65	0	8.4	<1	1	-	
	7/31/79	8.58	130	160	0.55	0.60	0.026	8.4	<1	1	-	
	8/13/79	-	-	-	0.23	0.30	0.02	-	<1*	17	-	
	8/28/79	8.62	144	156	0	0	0.01	-	<1	9	-	

*Unidentified pink-red colonies on MF plates

*Unidentified pink-red colonies on MF plates

TABLE 2.32 Water Quality Evaluations of Water Distribution System in Columbia MO (con't)

Sample Point	Date	Water Quality Parameters									
		pH	Alkalinity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Chlorine Residuals		Iron (mg/l)	D.O. (mg/l)	Coliform MF (no/100 ml)	Average SPC at 35°C (no/ml)	
					Free (mg/l)	Total (mg/l)				2 days	6 days
Raw Water	9/6/78	7.08	362	362	0	0	6.5	-	<1	1	1
	9/20/78	7.05	406	396	0	0	9.65	-	<1	1	2
	10/4/78	-	340	360	0	0	7.0	-	<1	2	1
	11/1/78	7.15	380	378	0	0	7.45	-	<1	0	0
	11/22/78	7.07	370	378	0	0	6.7	-	<1	0	-
	12/6/78	7.03	308	320	0	0	6.2	-	<1	0	1
	12/19/78	6.97	404	404	0	0	6.05	2.4	<1	2	3
	1/10/79	6.92	376	388	0	0	7.75	2.8	<1*	6	8
	1/31/79	7.11	402	390	0	0	5.95	2.8	<1	-	-
	2/14/79	7.31	444	450	0	0	7.85	-	<1*	1	1
	2/28/79	7.12	430	434	0	0	8.05	3.0	<1*	4	4
	3/14/79	7.18	366	374	0	0	8.25	2.2	<1	0	0
	4/4/79	7.16	386	394	0	-	7.45	3.7	<1*	3	3
	4/18/79	7.08	388	396	0	0	7.05	2.8	<1	0	0
	5/19/79	7.13	368	378	0	0	7.30	3.0	<1	16	-
	5/23/79	7.10	306	334	0	0	6.80	2.4	<1	0	-
	6/6/79	7.10	480	408	0	0	7.05	2.8	<1	28	28
	6/20/79	6.92	338	352	0	0	7.25	3.5	<1*	26	22
	7/4/79	7.04	348	336	0	0	8.60	2.6	<1	25	-
	7/16/79	6.93	332	328	0	0	6.05	1.7	<1	0	-
	7/31/79	7.33	360	368	0	0	-	2.6	<1	1	-
	8/13/79	7.02	408	400	0	0	7.10	3.0	<1	0	-
	8/28/79	7.07	392	392	0	0	5.25	2.5	<1	14	-

*Unidentified pink-red colonies on MF plates

TABLE 1.32 Water Quality Evaluations of Water Distribution System in Columbia MO (cont)

Sample Point	Water Quality Parameters										
	Date	pH	Alka- linity (mg/l as CaCO ₃)	Hard- ness (mg/l as CaCO ₃)	Chlorine Residuals		Iron (mg/l)	D.O. (mg/l)	Coliform MF (no/100 ml)	Average SPC	
					Free (mg/l)	Total (mg/l)				at 35°C 2 days	(no/ml) 6 days
Finished Water	9/6/78	8.44	126	136	4.40	4.55	0.068	-	<1	0	0
	9/20/78	9.43	118	118	5.05	5.10	0	-	<1	1	1
	10/4/78	8.70	150	154	1.20	1.35	0.004	-	<1	0	-
	11/1/78	8.43	168	160	0	0	0.004	-	<1	0	-
	12/6/78	9.01	128	134	3.00	3.02	0.014	-	<1	0	0
	12/19/78	8.85	142	150	1.10	1.15	0.002	9.6	<1	1	1
	1/10/79	9.0	124	156	1.60	1.72	0.002	10.0	<1	1	0
	1/31/79	8.57	166	166	1.52	1.60	0.004	10.0	<1	-	-
	2/14/79	9.05	154	152	1.60	1.60	0	-	<1	1	0
	2/28/79	8.68	150	154	1.50	1.70	1.47	9.8	<1	282	3
	3/14/79	8.94	130	157	1.68	1.75	0.006	9.6	<1	0	0
	4/4/79	9.27	110	138	1.90	2.00	0.006	10.0	<1	0	0
	4/18/79	8.93	116	142	2.55	2.60	0	9.8	<1	0	0
	5/19/79	9.11	116	140	1.20	1.40	0	9.1	<1	1	-
	5/23/79	8.27	144	176	2.30	2.45	0	9.3	<1	0	-
	6/6/79	8.53	130	200	0.70	0.75	0.35	9.2	<1	0	0
	6/20/79	8.32	136	168	1.70	1.70	0	9.2	<1	0	0
	7/4/79	8.61	146	162	1.90	2.00	0	9.4	<1	0	-
	7/16/79	9.07	136	130	0.90	0.90	0	9.2	<1	0	-
	7/31/79	8.36	154	146	0.81	0.85	0	9.2	<1	0	-
	8/13/79	9.02	132	136	1.85	1.95	-	9.3	<1	0	-
	8/28/79	8.70	154	152	1.25	1.30	0.006	9.4	<1	1	-
	6/20/79	8.32	136	168	1.70	1.70	0	9.2	<1	0	0
	7/4/79	8.61	146	162	1.90	2.00	0	9.4	<1	0	-
	7/16/79	9.07	136	130	0.90	0.90	0	9.2	<1	0	-
	7/31/79	8.36	154	146	0.81	0.85	0	9.2	<1	0	-
	8/13/79	9.02	132	136	1.85	1.95	-	9.3	<1	0	-
	8/28/79	8.70	154	152	1.25	1.30	0.006	9.4	<1	1	-

This high SPC value was accompanied by a zero chlorine residual. Total coliform counts were again less than one per 100 ml. However, a few samples showed the pink-red atypical coliform colonies.

Sample point No. 4 is located in the northeastern section of Columbia and is supplied by a 15 year old 15 cm (6 inch) C.I. main (unlined). Chlorine residuals were adequate for most of the sample period resulting in low SPC's (<100/ml). Only a few samples yielded the pink-red colonies in the membrane filter total coliform tests.

Sample point No. 5 was located at the Columbia Public Library in the central part of the town. The water main supplying this area was a 15 cm diameter cast iron main (unlined) installed some 30 years ago. Chlorine residuals were, for most of the sample period, high enough to maintain low SPC's. Only a few samples showed the pink-red colonies in the membrane filter total coliform tests. Total iron concentrations were low (<0.1 mg/l) throughout the sample period despite the fact that the finished water occasionally (2/28/79 and 6/6/79) had high iron concentrations (0.35 mg/l). Dissolved oxygen levels were high throughout the system. Variations in dissolved oxygen levels appeared to correspond to seasonal temperature changes. The hardness of the finished water varied inversely with the pH. The high hardness (>200 mg/l as CaCO_3) and alkalinity (>200 mg/l as CaCO_3) at sample point Nos. 3 & 4 were due to the influence of untreated hard water from the city's deep wells.

The longer (6-day) incubation period generally resulted in higher standard plate counts. Total phosphate levels in the distribution system were generally quite low (<0.21 mg/l). Orthophosphate concentrations in the distribution system were also low (<0.03 mg/l). Polyphosphates are added at the treatment plant to sequester and stabilize unprecipitated CaCO_3 . Polyphosphate (Nalco 918) dosages were approximately 0.5 mg/l as P.

In summary, the water quality in the distribution system of Columbia, Missouri was generally quite good. High chlorine residuals were maintained throughout the system most of the sample period. Standard plate counts were low except at a few locations (Sample Point No. 1 & 2). While there was no definite relationship between high standard plate counts and chlorine residuals, in some cases it was clear that zero or low chlorine residuals were associated with higher bacterial counts. Total coliform counts were always less than one per 100 ml. However, in many instances,

unidentified pink or red colonies were observed on the total coliform plates. The data indicates these organisms were disinfectant resistant bacteria. Total iron concentrations were low and dissolved oxygen concentrations high.

Tampa, Florida

The city of Tampa, Florida obtains water from two sources - surface supplies and ground water, through two treatment plants. The 30th Street Water Treatment Plant is supplied by surface water from the Hillsborough River, which has a 650 square mile drainage basin and many springs. The raw water quality fluctuates widely because of rainfall and the pumping of "sulfur springs" into the river to supplement the river. The Morris Bridge Water Treatment Plant has, as its source of supply, 20 wells. The treatment consists of lime softening, stabilization, filtration and disinfection. Treatment at the 30th Street Plant consists of alum coagulation flocculation with "activated" sodium silicate as a coagulant aid, settling, filtration and chlorine disinfection. Lime is used for pH adjustment and stabilization.

The types of water quality problems in the distribution system are varied. In some sections, older tuberculated water mains cause "red water" complaints, in some dead-end mains, calcium carbonate and alum sludge buildup causes sediment problems, and construction and repair of mains causes complaints of suspended particles in water.

Sample locations Nos. 1, 2, 3 and 4 receive water from the 30th Street Plant, while sample location No. 6 receives water from both the 30th Street and Morris Bridge Plants. Sample point No. 5 receives water exclusively from the Morris Bridge Plant. Water quality data for the period June 1979 through May 1980 are provided in Table 33.

Drastic losses in chlorine residuals were observed at sample points Nos. 3 and 4 on many occasions. Depletions of chlorine residuals were not as large at sample point Nos. 1 and 2. Sample points 5 and 6 usually had adequate residuals throughout the sampling period. The loss of chlorine residuals were more pronounced as water temperatures increased. Recalling that sampling points 1-4 are supplied from the surface water treatment plant, while sampling point 5 is supplied from a ground water treatment plant and sampling point 6 can be supplied from either plant, it appears that the chlorine residuals do not persist in the distribution system when the supply is from the surface source. Coliform bacteria were generally absent throughout the distribution system, despite the fact that at several locations, there were

TABLE 5.33 Water Quality Evaluation of Water Distribution System in Tampa, FL

Sample Point	Date	pH	Alkalinity (mg/l CaCO ₃ eq.)	Hardness (mg/l CaCO ₃ eq.)	Total Iron (mg/l)	Turbidity	Mn (mg/l)	Water Temp. (°F)	Chlorine Residual (mg/l Cl)	Coliform (MF/100 ml)	Total Plate Count (2 Days at 35°C) (#/ml)
1	6/16/79	7.51	91	194	0.55	0.29	<0.01	86	0.0	0	0
	7/3/79	7.78	89	190	0.77	0.30	-	89	0.2	0	0
	8/27/79	7.45	52	126	0.18	1.25	<0.01	86	0	0	155
	9/4/79	7.40	43	112	0.06	0.48	0.02	83	0.5	0	12
	10/22/79	7.41	67	154	0.38	0.25	<0.01	80	0.7	0	0
	11/26/79	7.40	106	212	1.03	0.14	<0.01	72	1.8	0	0
	12/17/79	7.60	110	210	0.003	0.24	0.02	71	1.6	0	0
	1/28/80	7.70	107	182	0.09	0.28	<0.01	58	1.8	0	0
	2/25/80	7.54	102	178	0.08	0.26	<0.01	70	0.2	0	2
	3/24/80	7.75	94	172	0.06	0.52	<0.01	72	1.5	0	0
	4/28/80	7.58	77	158	0.19	0.66	<0.01	78	0.5	0	0
	5/28/80	7.65	95	168	0.05	0.19	0.02	80	0.8	0	0
2	6/26/79	7.50	90	200	0.06	0.31	<0.01	90	0.6	0	1
	7/30/79	7.78	91	190	0.10	0.30	-	91	0.2	0	0
	8/27/79	7.45	54	126	1.00	0.60	0.05	88	0	3	60
	9/24/79	7.30	41	112	0.26	0.39	0.02	86	0	0	2000
	10/22/79	7.48	67	154	0.34	0.21	<0.01	84	0.1	0	10
	11/26/79	7.78	105	218	0.29	0.16	<0.01	77	0.8	0	20
	12/17/79	7.68	110	212	0.002	0.17	0.02	72	1.1	0	0
	1/28/80	7.71	100	178	0.06	0.21	<0.01	70	0.5	0	0
	2/25/80	7.65	102	176	0.04	0.30	<0.01	72	0.4	0	1
	3/24/80	7.70	95	180	<0.01	0.25	<0.01	76	0.2	0	5
	4/28/80	7.60	79	160	0.13	0.34	<0.01	80	0	0	10
	5/28/80	7.80	93	160	0.12	0.11	0.02	85	0.5	0	0

TABLE 33 Water Quality Evaluation of Water Distribution System in Tampa FL (con't)

Sample Point	Date	pH	Alkalinity (mg/l CaCO ₃ eq.)	Hardness (mg/l CaCO ₃ eq.)	Total Iron (mg/l)	Turbidity	Mn (mg/l)	Water Temp. (°F)	Chlorine Residual (mg/l Cl)	Coliform (MF/100 ml)	Total Plate Count (2 Days at 35°C) (#/ml)
3	6/27/79	7.63	95	196	0.37	0.43	<0.01	87	0	0	700
	7/30/79	7.85	91	194	0.07	0.29	-	88	0	0	18000
	8/27/79	7.60	54	126	0.58	0.70	<0.01	84	0	0	30
	9/24/79	7.45	40	108	0.11	1.0	0.02	83	1.0	0	0
	10/22/79	7.65	64	154	0.38	0.66	<0.01	83	0.2	0	212
	11/26/79	7.90	98	214	0.79	0.27	<0.01	77	0.4	0	0
	12/17/79	7.90	113	212	0.006	0.28	0.02	72	0.2	0	2
	1/28/80	7.86	103	178	0.27	0.30	<0.01	68	0	0	0
	2/25/80	7.80	104	180	0.07	0.31	<0.01	70	0.3	0	2
	3/24/80	7.75	97	178	0.30	6.80	0.04	73	0.3	0	1
4	4/28/80	7.56	80	160	0.07	0.30	<0.01	78	0	0	6
	5/28/80	8.05	97	160	0.06	0.19	0.02	83	0	0	12
	6/27/79	7.65	91	192	0.23	0.24	<0.01	82	0	1	1300
	8/1/79	7.63	97	198	0.05	0.23	-	85	0	0	390
	8/27/79	7.65	56	130	0.18	0.30	<0.01	84	0	0	195
	9/25/79	7.60	44	114	0.06	0.39	0.02	84	0	0	0
	10/23/79	7.65	71	156	0.20	0.23	<0.01	80	0	0	5200
	11/27/79	7.81	115	212	0.32	0.62	<0.01	75	0	0	6
	12/17/79	7.80	114	212	0.004	0.18	0.02	72	0.1	0	15
	1/28/80	7.89	105	184	0.15	0.46	<0.01	68	0.2	0	20
	2/26/80	7.81	100	176	0.07	0.41	<0.01	67	0.3	0	50
	3/24/80	7.88	98	174	0.01	0.24	<0.01	72	0	0	0
	4/29/80	7.70	79	166	0.15	0.37	<0.01	76	0	0	10
	5/28/80	7.98	97	160	0.02	0.14	0.02	80	0	0	7

TABLE 33 Water Quality Evaluation of Water Distribution System in Tampa, FL (con't)

Sample Point	Date	pH	Alkalinity (mg/l CaCO ₃ eq.)	Hardness (mg/l CaCO ₃ eq.)	Total Iron (mg/l)	Turbidity	Mn (mg/l)	Water Temp. (°F)	Chlorine Residual (mg/l Cl)	Coliform (MF/100 ml)	Total Plate Count (2 Days at 35°C) (#/ml)
5	6/26/79	7.70	158	174	0.28	0.91	<0.01	86	1.8	0	0
	8/1/79	7.71	133	166	0.04	0.53	-	85	1.7	0	0
	8/29/79	7.80	120	156	0.32	0.10	<0.01	82	0.6	0	0
	9/25/79	7.65	111	146	0.26	0.64	0.02	82	0.9	0	0
	10/23/79	7.80	135	162	0.14	0.37	<0.01	79	1.3	0	0
	11/27/79	7.93	137	166	0.02	0.59	<0.01	73	0.9	0	0
	12/18/79	8.10	143	154	0.003	0.68	0.02	70	1.1	0	0
	1/29/80	7.87	150	174	0.05	1.10	<0.01	67	1.3	0	0
	2/26/80	7.86	113	144	0.05	0.63	<0.01	67	0.5	0	2
	3/25/80	7.88	151	168	0.01	0.67	<0.01	72	1.1	0	0
6	4/29/80	7.80	145	168	0.07	0.87	<0.01	76	1.0	0	0
	5/27/80	7.91	153	170	0.03	0.14	0.02	80	0.7	0	1
	6/27/79	7.34	137	166	1.19	0.18	0.003	86	0.4	0	2
	8/1/79	7.72	129	172	0.05	0.35	-	86	0.6	0	23
	8/9/79	7.70	63	140	0.27	1.40	<0.01	86	0	0	125
	9/25/79	7.61	150	168	0.11	0.32	0.02	82	1.3	0	15
	10/23/79	7.80	138	160	0.33	0.44	<0.01	82	1.8	0	0
	11/27/79	7.92	126	186	0.02	0.33	<0.01	76	0.8	0	0
	12/18/79	7.91	114	174	0.003	0.28	0.02	70	1.3	0	0
	1/29/80	7.69	142	164	0.05	0.31	<0.01	69	1.3	0	0
	2/25/80	7.70	106	174	0.01	0.31	<0.01	70	0.2	0	3
	3/25/80	7.90	125	166	0.01	0.36	<0.01	74	0.8	0	0
	4/28/80	7.85	132	150	0.02	0.13	<0.01	77	2.0	0	0
	5/27/80	7.88	126	168	0.07	0.60	0.02	80	0.3	0	3

TABLE 33 Water Quality Evaluation of Water Distribution System in Tampa, FL (con't)

Sample Point	Date	pH	Alkalinity (mg/l CaCO ₃ eq.)	Hardness (mg/l CaCO ₃ eq.)	Total Iron (mg/l)	Turbidity	Mn (mg/l)	Water Temp. (°F)	Chlorine Residual (mg/l Cl)	Coliform (MF/100 ml)	Total Plate Count (2 Days at 35°C) (#/ml)
Raw	6/26/79	7.11	88	124	0.23	0.93	0.021	82	0	17500	11500
Water	7/31/79	7.38	89	124	0.11	0.81	0.013	83	0	12500	1250
30th	8/27/79	6.56	44	64	0.28	1.25	0.009	79	0	250	250
Street	9/24/79	6.65	34	50	0.67	2.75	0.017	78	0	38000	3500
Bridge	10/23/79	6.95	67	88	0.54	0.95	0.015	76	0	19000	8500
(Surface	11/27/79	7.17	122	160	0.29	0.92	0.028	69	0	40000	8500
Water	12/17/79	7.69	119	164	0.22	1.25	0.019	67	0	105000	8500
Source)	1/29/80	7.59	102	128	0.15	1.90	0.009	64	0	17000	19500
	2/26/80	7.75	105	128	0.10	1.20	0.006	66	0	10300	87500
	3/24/80	7.65	105	124	0.15	1.75	0.041	72	0	25000	40000
	4/28/80	7.48	77	106	0.24	1.80	0.020	74	0	14000	5000
	5/28/80	8.32	99	120	0.14	0.85	0.010	81	0	12800	25000
Raw	6/26/79	7.20	268	272	0.14	0.51	0.011	78	0	0	0
Water	7/30/79	7.15	268	262	0.19	0.83	0.016	78	0	0	-
Morris	8/29/79	7.40	247	272	0.09	0.54	0.009	77	0	1	-
Bridge	9/24/79	7.16	267	266	0.067	0.27	0.011	73	0	0	0
Plant	10/23/79	7.29	268	270	0.053	0.34	0.008	74	0	1	0
(Ground	11/27/79	7.23	122	160	0.18	0.34	0.013	75	0	0	0
Water	12/17/79	7.46	266	272	0.083	0.34	0.010	76	0	0	0
Source)	1/29/80	7.27	261	266	0.01	0.46	0.006	75	0	0	0
	2/26/80	7.31	256	266	0.01	0.62	0.008	75	0	0	16000
	3/24/80	7.30	260	266	0.077	0.59	0.008	75	0	0	2
	4/28/80	7.29	260	266	0.11	0.61	<0.01	76	0	0	0
	5/28/80	7.25	258	260	0.14	0.66	0.006	76	0	0	6

TABLE 33 Water Quality Evaluation of Water Distribution System in Tampa FL (con't)

Sample Point	Date	pH	Alkalinity (mg/l CaCO ₃ eq.)	Hardness (mg/l CaCO ₃ eq.)	Total Iron (mg/l)	Turbidity	Mn (mg/l)	Water Temp. (°F)	Chlorine Residual (mg/l Cl)	Coliform (MF/100 ml)	Total Plate Count (2 Days at 35°C) (#/ml)
Finished Water 30th Street Plant	6/26/79	7.63	83	194	<0.01	0.24	0.009	84	2.7	0	0
	7/31/79	7.70	95	192	0.05	0.48	0.005	85	2.7	0	0
	8/27/79	7.32	53	128	0.039	0.41	0.004	81	2.4	0	0
	9/24/79	7.42	41	106	0.067	0.39	0.006	80	3.3	0	0
	10/23/79	7.51	70	156	0.003	0.16	0.003	78	3.5	0	0
	11/27/79	7.50	110	210	0.023	0.24	0.008	71	3.6	0	0
	12/17/79	7.70	109	210	0.023	0.19	0.004	69	3.1	0	0
	1/29/80	7.90	100	174	0.012	0.27	<0.001	66	2.4	0	0
	2/26/80	7.52	98	170	0.018	0.28	0.002	68	2.4	0	0
	3/24/80	7.62	96	174	0.007	0.33	0.004	74	2.4	0	0
	4/28/80	7.52	80	162	0.060	0.26	<0.010	75	2.6	0	0
	5/28/80	7.82	93	158	0.019	0.26	<0.020	83	3.0	0	0
Finished Water Morris Bridge Plant	6/26/79	-	147	158	0.140	0.39	0.003	78	3.2	0	0
	7/30/79	7.42	146	154	0.020	0.95	0.004	78	2.2	0	-
	8/29/79	7.70	142	156	0.021	0.16	0.003	78	2.5	0	-
	9/24/79	7.65	155	168	0.036	0.26	0.004	78	2.7	0	0
	10/23/79	7.75	154	162	0.001	0.16	0.002	73	2.6	0	0
	11/27/79	7.71	145	154	0.180	0.22	0.018	77	2.6	0	0
	12/17/79	8.01	140	150	0.022	0.23	0.002	76	2.6	0	0
	1/29/80	7.82	154	164	0.070	0.26	0.006	76	2.4	0	0
	2/26/80	7.75	121	134	0.019	0.27	0.001	74	2.8	0	0
	3/24/80	7.75	149	162	0.012	0.21	0.001	77	2.4	0	0
	4/28/80	7.70	136	152	0.020	0.34	<0.010	77	2.5	0	0
	5/28/80	7.71	146	158	0.014	0.23	<0.020	77	2.5	0	0

no detectable chlorine residuals. Only two samples (Sample Point No. 2, 8/27/79 and Sample Point No. 4, 6/27/79) showed coliforms to be present and, in both instances, the chlorine residuals were zero. The absence of coliform may indicate good microbial raw water quality. However, the lack of chlorine residual and high water temperatures in the system appears to permit the growth and persistence of bacteria as evidenced by high SPC values. Sampling points Nos. 2 and 3 occasionally yielded high SPC values, while Sampling points 1, 5 and 6 exhibited quite low SPC values. The high microbial counts in the finished water from the 30th Street Plant on 4/28/80 did not appear to result in high counts at the distribution system sample points.

There was some evidence that the total iron concentrations in the distribution system was increasing, possibly as the result of pipe corrosion. Sampling points 1, 2, 3, 4 and 6 showed evidence, at least in one instance, of total iron levels greater than the aesthetic limit of 0.3 mg/l despite the fact that the treated water iron levels were always less than 0.18 mg/l. High iron concentrations generally did not correspond with high turbidity levels (except in Sample 3, on 3/24/80). Total hardness and alkalinity varied from point to point principally depending upon the source of the supply to the particular point. Manganese values were very low (<0.02 mg/l Mn) throughout the system.

In summary, the microbial water quality in the Tampa, Florida distribution system as measured by SPC's was directly affected by the loss of chlorine residuals. Chlorine residuals did not persist in the portion of the system supplied by the surface source (30th Street Plant). There was some evidence of total iron increases in the system caused by corrosion of the pipelines.

Minneapolis, Minnesota

The Minneapolis, Minnesota water source is the Mississippi River. The raw water is pumped to two filtration plants, the Fridley and Columbia Heights plants. The capacity of the Fridley and Columbia Heights plants is 80 mgd and 78 mgd, respectively. The water is softened prior to filtration. Minneapolis is ringed by a 1.22m diameter main which supplies the city from the outside in. Water quality data from four sample points in the distribution system as well as the raw and the finished water were evaluated.

Most of the water quality complaints presumably due to the stirring up of the sediments in the mains caused by high velocities when fire hydrants were opened. These sediments were usually post-precipitated gray-black alum flocs. In a

few isolated areas, rusty water problems occur. Some of the areas having rusty water are from dead-end mains which have not yet been looped.

Color is a major problem for water utilities using Mississippi River water. During the spring periods of heavy rain, raw Mississippi River water color tends to increase to 100 units or higher. The increased alum doses required to treat the water depresses the pH, making it more corrosive.

Table 34 presents the water quality data from the Minneapolis water distribution system for the period September 1978 to August 1979. Sample points Nos. 3 and 10 were being supplied from the Fridley Filtration Plant, while Sample points Nos. 6 and 13 were being supplied from the Columbia Heights Filtration Plant. The water quality data in Table 34, for the period September 1978 through February 1979, are monthly average values, while the data from February 26, 1979 and thereafter are individual values for that sampling date.

Dissolved oxygen concentrations were high throughout the Minneapolis distribution system. Low oxygen levels in summer months are related to warmer temperatures which reduced the oxygen saturation level. Combined chlorine concentrations did not change significantly in the distribution system although concentrations varied from 1.8 to 3.7 mg/l. Consequently, the coliform MPN values were always less than 2.2 per 100 ml (and sometime <2.2 per 50 ml) indicating satisfactory bacteriological quality. The standard plate counts were generally low (<50 per ml) except occasionally at sample point No. 3. Previously, sample point No. 3 was near a dead-end main which usually had a poorer water quality. In the summer of 1978, the dead end was looped, thereby increasing the chlorine residual persistence. Still, SPC values are occasionally high. Chlorination and main flushing may be necessary to control the localized bacterial problems.

Standard Plate Counts were measured at 20°C and 35°C for each sample. Generally, the 20°C SPC values were higher than the 35°C values. Iron concentrations in the distribution system were quite low (<0.06 mg/l). All other water quality parameters are quite satisfactory.

Sioux Falls, South Dakota

The major source of water supply for Sioux Falls, South Dakota is ground water. While there are two surface intakes on the Big Sioux River diversion canal, the city primarily depends on a field of 32 wells to provide the water needed. The raw water is pumped to the treatment plant where anionic polymers are first added to assist flocculation and then

TABLE 34 Water Quality Evaluations of Water Distribution System in Minneapolis, MN

Sample Point	Water Quality Parameters											
	pH	Alka- linity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Combined Chlorine Resid. (mg/l)	NH ₄ ⁺ (mg/l as N)	NO ₃ ⁻ (mg/l as N)	Iron (mg/l)	Sulfate (mg/l)	D.O. (mg/l)	Coliform MPN/100 ml	SPC 350C (no/ml)	SPC 200C (no/ml)
3	9/78	-	-	1.9	-	-	-	-	-	<2.2/50 ml	79	-
	10/78	-	-	2.0	-	-	-	-	-	<2.2/50 ml	60	-
	11/78	-	-	2.0	-	-	-	-	-	<2.2/50 ml	174	-
	12/78	-	-	2.0	-	-	-	-	-	<2.2/50 ml	82	-
	1/79	-	-	1.8	-	-	-	-	-	<2.2/50 ml	81	-
	2/79	-	-	2.0	-	-	-	-	-	<2.2/50 ml	19	-
	2/26/79	40	69	2.5	1.30	0.57	0.05	28	13.7	<2.2	30	32
	3/12/79	45	77	2.4	1.08	0.47	0.03	29	14.1	<2.2	13	20
	3/26/79	41	78	2.9	1.28	0.80	0.03	34	13.1	<2.2	35	45
	4/9/79	49	91	2.5	1.64	1.05	0.03	37	13.4	<2.2	12	3
	4/23/79	41	84	2.9	1.25	0.65	0.01	39	11.4	<2.2	5	7
	5/7/79	42	80	2.7	1.28	0.15	0.04	31	11.3	<2.2	6	10
	5/21/79	29	74	2.1	1.11	0.50	0.03	34	9.4	<2.2	10	-
6/5/79	31	64	2.6	1.46	0.18	0.03	38	8.7	<2.2	7	14	
6/18/79	8.29	36	68	1.97	0.24	0.02	25	9.2	<2.2	1	0	
7/9/79	8.14	40	72	3.1	1.30	0.31	<0.01	23	8.2	<2.2	2	7
7/23/79	8.18	38	69	3.3	1.50	0.38	<0.01	23	7.5	<2.2	0	0
8/6/79	8.44	37	67	2.7	1.70	0.36	0.01	23	7.6	<2.2	112	180
8/20/79	8.40	37	71	3.1	1.35	0.43	<0.01	30	8.8	<2.2	72	110
6	9/78	-	-	1.8	-	-	0.04	-	-	<2.2/50 ml	2	-
	10/78	-	-	2.2	-	-	0.04	-	-	<2.2/50 ml	1	-
	11/78	-	-	2.0	-	-	0.01	-	-	<2.2/50 ml	1	-
	12/78	-	-	2.0	-	-	0.01	-	-	<2.2/50 ml	2	-
	1/79	-	-	1.9	-	-	0.01	-	-	<2.2/50 ml	1	-
	2/79	-	-	1.8	-	-	<0.01	-	-	<2.2/50 ml	5	-

TABLE 34 Water Quality Evaluations of Water Distribution System in Minneapolis, MN (con't)

Sample Point	Date	pH	Water Quality Parameters										SPC _{35°C} (no/ml)	SPC _{20°C} (no/ml)
			Alkalinity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Combined Chlorine Resid. (mg/l)	NH ₄ ⁺ (mg/l as N)	NO ₃ ⁻ (mg/l as N)	Iron (mg/l)	Sulfate (mg/l)	D.O. (mg/l)	Coliform MPN/100 ml			
6 (con't)	2/26/79	8.23	42	70	3.1	1.45	0.62	0.05	25	13.9	< 2.2		0	0
	3/12/79	8.32	43	73	2.7	1.26	0.51	0.02	27	14.1	< 2.2		1	0
	3/26/79	8.51	43	71	2.7	1.25	0.67	0.01	24	13.1	< 2.2		3	2
	4/9/79	8.10	50	92	3.2	1.56	1.45	0.03	34	13.1	< 2.2		-	-
	4/23/79	7.58	41	82	2.9	1.29	0.79	0.04	38	11.7	< 2.2		2	5
	5/7/79	7.66	43	75	2.9	1.27	0.28	0.05	33	10.6	< 2.2		2	1
	5/21/79	7.52	26	68	2.8	1.17	0.40	0.03	34	9.9	< 2.2		0	-
	6/5/79	7.64	25	56	3.1	1.40	0.19	0.04	29	9.1	< 2.2		0	0
	6/18/79	7.91	31	60	3.2	1.70	0.20	0.02	25	8.3	< 2.2		0	4
	7/9/79	7.98	35	63	3.2	1.32	0.35	< 0.01	27	8.1	< 2.2		1	1
	7/23/79	7.97	36	66	3.5	1.54	0.39	0.02	24	7.8	< 2.2		1	3
	8/6/79	7.94	37	66	3.2	1.69	0.35	0.06	21	8.2	< 2.2		3	12
	8/20/79	8.06	33	64	3.7	1.61	0.32	< 0.01	25	8.8	< 2.2		0	0
10	9/78	7.9	40	-	2.5	-	-	0.03	-	-	< 2.2/50 ml		5	-
	10/78	8.13	42	-	2.4	-	-	0.04	-	-	< 2.2/50 ml		51	-
	11/78	8.4	47	-	2.6	-	-	0.03	-	-	< 2.2/50 ml		2	-
	12/78	8.48	45	-	2.4	-	-	0.02	-	-	< 2.2/50 ml		1	-
	1/79	8.53	46	-	2.2	-	-	0.01	-	-	< 2.2/50 ml		1	-
	2/79	8.35	44	-	2.4	-	-	0.01	-	-	< 2.2/50 ml		18	-
	2/26/79	8.33	39	70	2.7	1.60	0.54	0.03	29	13.9	< 2.2		0	0
	3/12/79	8.22	45	79	2.4	1.12	0.50	0.03	28	14.1	< 2.2		0	2
	3/26/79	7.98	40	79	3.0	1.24	0.75	0.03	35	13.0	< 2.2		3	4
	4/9/79	7.66	51	94	2.5	1.48	1.40	0.02	39	13.1	< 2.2		21	23
	4/23/79	7.64	41	85	2.9	1.29	0.64	0.01	38	11.6	< 2.2		6	3
	5/7/79	7.75	43	81	2.7	1.22	0.15	0.02	32	10.7	< 2.2		3	4

TABLE 34 Water Quality Evaluations of Water Distribution System in Minneapolis, MN (con't)

Sample Point	Date	pH	Water Quality Parameters										
			Alka- linity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Combined Chlorine Resid. (mg/l)	NH ₄ ⁺ (mg/l as N)	NO ₃ ⁻ (mg/l as N)	Iron (mg/l)	Sulfate (mg/l)	D.O. (mg/l)	Coliform MPN/100	SPC 35°C (no/ml)	SPC 20°C (no/ml)
10 (con't)	5/21/79	7.79	29	75	2.4	1.22	0.38	0.01	34	9.6	<2.2	2	-
	6/5/79	8.06	33	68	2.8	1.37	0.19	0.02	28	9.1	<2.2	0	1
	6/18/79	8.50	37	72	3.0	1.56	0.22	0.02	26	8.1	<2.2	3	9
	7/9/79	8.25	41	72	3.1	1.46	0.32	0.01	23	8.1	<2.2	1	1
	7/23/79	8.34	38	68	3.6	1.61	0.37	<0.01	25	7.5	<2.2	4	6
	8/6/79	8.58	39	67	3.4	1.88	0.35	<0.01	23	7.9	<2.2	0	0
	8/20/79	8.50	36	72	3.6	1.62	0.43	<0.01	30	8.9	<2.2	0	0
13	9/78	7.85	40	-	2.2	-	-	-	-	-	<2.2/50 ml	4	-
	10/78	8.01	37	-	2.4	-	-	-	-	-	<2.2/50 ml	0	-
	11/78	8.29	43	-	2.8	-	-	-	-	-	<2.2/50 ml	4	-
	12/78	8.69	44	-	2.4	-	-	-	-	-	<2.2/50 ml	2	-
	1/79	8.66	45	-	2.2	-	-	-	-	-	<2.2/50 ml	0	-
	2/79	8.40	43	-	2.5	-	-	-	-	-	<2.2/50 ml	0	-
	2/26/79	8.11	41	70	3.1	1.32	0.47	0.03	24	13.2	<2.2	0	0
	3/13/79	8.28	41	68	2.6	1.18	0.53	0.02	26	13.4	<2.2	2	3
	3/26/79	8.37	43	73	2.6	1.27	0.70	0.03	28	13.2	<2.2	3	4
	4/9/79	7.92	49	91	2.9	1.47	0.96	0.02	36	13.2	2.2	13	19
	4/23/79	7.57	40	82	2.9	1.41	0.79	0.01	38	11.9	2.2	6	7
	5/7/79	7.77	43	74	3.2	1.26	0.26	0.01	32	11.0	2.2	0	0
	5/21/79	7.65	27	68	2.5	1.21	0.40	0.01	35	10.0	2.2	7	-
	6/5/79	7.67	25	58	2.8	1.43	0.19	0.01	27	8.9	2.2	0	2
	6/18/79	7.93	30	61	2.7	1.60	0.21	0.01	23	8.1	2.2	6	10
	7/9/79	8.05	35	63	2.8	1.33	0.36	<0.01	22	8.2	2.2	0	0
7/23/79	8.05	37	67	3.5	1.54	0.38	<0.01	24	7.7	2.2	0	0	
8/6/79	8.10	36	65	2.9	1.49	0.35	<0.01	23	8.0	2.2	0	2	
8/20/79	8.15	35	64	3.6	1.55	0.32	0.02	25	9.0	2.2	0	3	

TABLE 34 Water Quality Evaluations of Water Distribution System in Minneapolis, MN (con't)

Point	Date	pH	Water Quality Parameters										
			Alka- linity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Combined Chlorine Resid. (mg/l)	NH ₄ ⁺ (mg/l as N)	NO ₃ ⁻ (mg/l as N)	Iron (mg/l)	Sulfate (mg/l)	D.O. (mg/l)	Coliform MPN/100 ml	SPC 35°C (no/ml)	SPC 20°C (no/ml)
Raw Water	9/7	8.12	124	144	-	0.51	0.63	0.2	9.79	-	2758	3161	4483
	10/78	8.42	147	166	-	0.58	0.20	0.16	12.20	-	622	516	1672
	11/78	8.53	158	176	-	0.20	0.32	0.11	12.98	-	413	307	1381
	12/78	8.15	178	200	-	0.62	0.47	0.13	15.00	-	290	199	1552
	1/79	7.94	178	198	-	0.41	0.40	0.13	12.40	-	276	341	903
	2/79	7.76	175	191	-	0.43	0.38	0.12	12.92	-	239	271	1159
	2/26/79	8.12	172	189	-	0.43	0.38	0.30	16	13.8	460	180	1100
	3/12/79	8.24	170	190	-	0.54	0.41	0.28	11	14.3	230	54	780
	3/26/79	8.19	155	178	-	0.80	1.12	0.59	13	13.4	2100	2600	93000
	4/9/79	7.90	116	149	-	0.81	1.27	0.65	17	13.0	1100	1500	2400
	4/23/79	7.94	88	106	-	0.48	0.52	1.23	10	11.1	2300	1100	15000
	5/7/79	8.18	101	116	-	0.27	0.07	0.57	10	10.3	1300	570	1300
	5/21/79	8.11	109	128	-	0.47	0.20	0.39	10	9.0	1700	850	2800
	6/5/79	8.29	135	148	-	0.80	0.13	0.50	10	8.3	400	410	1600
	6/18/79	8.28	141	158	-	0.35	0.36	0.65	8	8.2	3500	2400	3400
	7/9/79	8.25	146	160	-	0.35	0.24	0.78	5	7.9	4900	1100	2000
	7/23/79	8.26	148	161	-	0.25	0.30	0.36	8	6.9	450	2200	2600
	8/6/79	8.47	162	171	-	0.42	0.25	0.15	12	6.6	780	2800	5000
	8/20/79	8.35	169	187	-	0.24	0.47	0.18	14	7.2	130	470	970
Treat- ed	9/78	7.92	38	85	4.1	1.16	0.53	0.04	38	-	<1	-	-
	10/78	8.26	41	41	3.8	1.12	0.13	0.01	28	-	<1	-	-
	11/78	8.48	48	48	4.0	1.24	0.40	0.04	23	-	<1	-	-
	12/78	8.56	48	48	3.6	1.12	0.49	0.02	28	-	<1	-	-
1/79	8.47	50	50	3.4	1.40	0.39	0.01	0.01	26	-	<1	-	-
	2/79	8.38	42	42	3.3	1.31	0.38	0.02	25	-	<1	-	-

TABLE 34 Water Quality Evaluations of Water Distribution System in Minneapolis, MN (con't)

Point	Date	pH	Water Quality Parameters										
			Alka- linity (mg/l as CaCO ₃)	Hardness (mg/l as CaCO ₃)	Combined Chlorine Resid. (mg/l)	NH ₄ ⁺ (mg/l as N)	NO ₃ ⁻ (mg/l as N)	Iron (mg/l)	Sulfate (mg/l)	D.O. (mg/l)	Coliform MPN/100	SPC 35°C (no/ml)	SPC 20°C (no/ml)
Treated Water (con't)	2/26/79	8.41	37	68	3.3	1.31	0.38	0.04	29	14.5	2.2	0	0
	3/12/79	8.51	44	73	3.1	1.06	0.48	0.02	28	14.1	2.2	0	0
	3/26/79	7.97	36	75	3.5	1.31	0.82	0.01	35	13.8	2.2	0	0
	4/9/79	7.55	50	91	3.0	1.77	1.48	0.01	35	13.4	2.2	36	30
	4/23/79	7.67	42	83	3.6	1.24	0.64	0.03	40	12.0	2.2	-	-
	5/7/79	7.58	40	79	3.3	1.10	0.23	0.03	32	11.1	2.2	4	4
	5/21/79	7.76	31	73	2.9	1.26	0.31	0.02	35	10.1	2.2	0	-
	6/5/79	8.07	32	67	3.3	1.55	0.17	0.03	29	10.6	2.2	0	0
	6/18/79	8.23	42	73	3.5	1.93	0.30	0.01	25	8.2	2.2	1	1
	7/9/79	8.10	39	69	3.6	1.58	0.30	0.02	24	8.5	2.2	0	0
	7/23/79	8.24	45	75	3.6	1.63	0.37	0.01	24	9.6	2.2	1	1
	8/6/79	8.47	41	69	3.3	1.61	0.34	0.01	23	8.3	2.2	3	1?
	8/20/79	8.41	35	70	3.6	1.54	0.49	0.01	31	8.9	2.2	0	1

chlorine is added for disinfection. The water is then lime-treated to reduce the hardness and precipitate iron and manganese. The iron, manganese and calcium carbonate and oxides precipitated is removed in the solids contact basins. The lime-treated water then passes on to a recarbonation basin where pH is adjusted by CO₂ addition. Fluoride and polyphosphates are also added in the recarbonation basin. Polyphosphate (Nalco 918) is added at a dose of 1 mg/l to prevent CaCO₃ precipitation in the filters and in the distribution system. The water leaving the recarbonation basin is again chlorine disinfected before multi-media filtration. The filtered water after storage is pumped to the distribution system.

The water quality problems encountered in the distribution system are: lack of persistent chlorine residuals in certain areas and high iron concentrations.

The water quality changes in the distribution system were evaluated from sampling at six locations. Water quality data for the period May 1979 through April 1980 are presented in Table 35. Although the sampling period covered one calendar year the water quality data for some months were unavailable (September 1979 through December 1979).

Generally, total chlorine residuals persist throughout the Sioux Falls distribution system, although there are some marked declines in the residuals at sample points J4 and J5. In addition, on January 15, 1980 there was no residual chlorine at sample point J3. Although the sample points, J2 and J6, are fairly remote from the treatment plant, the total chlorine residuals did not decline as much as those at other sampling points. The water quality near sample point J3 is occasionally diminished due to the poor water circulation.

Standard plate counts did not follow any particular trend. Even when a total chlorine residual was absent (Sample Point J3, 1/15/80), the SPC was quite low. On the other hand, a high SPC, (690 per ml) was recorded when the total chlorine residual was 0.5 mg/l (Sample point J3, 6/27/79). However, in several samples, very low chlorine residuals accompanied high SPC's (Sample Point J5, 6/19/79 and 8/15/79). High total chlorine residuals at the sample points, J2 and J6, produced low SPC's (<33/ml).

Sample points J3, J4 and J6 occasionally showed high iron concentrations, once again confirming the chronic problem observed at Sioux Falls.

Since the treated water is consistently low in iron, this suggests that the corrosion of water mains or the solution of

TABLE 35 Water Quality Evaluations of Water Distribution System in Sioux Falls,
South Dakota

Sample Point	Date	Temp. °C	D.O. (mg/l)	pH	Chlorine Free (mg/l)	Chlorine Resid. Total (mg/l)	Total Iron (mg/L)	Hardness (mg/l as CaCO ₃)	Alka- linity (mg/l as CaCO ₃)	Spec. Cond.	Mn (mg/l)	SPC (no/ml)
J1 Finished Water at Treat- ment Plant	5/30/79	15	7.12	9.40	1.4	2.2	<0.05	330	32	550	0.02	<1
	6/6/79	12	7.00	9.25	0.8	2.6	<0.05	340	29	510	0.02	2
	6/13/79	12	7.00	9.10	1.3	2.1	<0.05	310	50	520	0.02	2
	6/19/79	11	-	9.30	1.4	1.8	<0.05	310	56	540	0.02	4
	6/27/79	13	6.73	9.35	1.5	2.0	<0.05	350	48	600	0.02	2
	7/11/79	13	6.09	9.00	1.1	2.5	<0.05	340	55	550	0.02	16
	7/24/79	13	-	9.35	1.5	1.9	<0.05	320	35	480	0.02	27
	7/31/79	16	-	9.15	1.4	1.9	0.12	310	35	600	0.02	-
	8/15/79	16	-	9.10	1.5	2.1	<0.05	350	31	540	0.02	2
	1/15/80	-	9.5	8.83	-	2.0	<0.05	400	26	600	0.02	6
	2/5/80	-	-	9.48	-	-	<0.05	342	32	560	0.02	10
	4/8/80	-	6.9	9.20	-	1.8	<0.05	410	38	550	0.02	47
J2	5/30/79	12	7.65	8.75	1.2	1.8	<0.05	340	20	660	0.02	4
	6/6/79	15	6.40	9.15	1.0	2.6	-	330	36	640	-	<1
	6/13/79	15	7.50	8.70	1.1	2.4	<0.05	320	50	680	0.02	<1
	9/19/79	16	-	9.45	1.2	1.6	0.05	320	43	480	0.02	1
	6/27/79	16	7.43	9.30	1.0	1.4	<0.05	340	39	580	0.02	<1
	7/11/79	18	6.98	9.10	1.0	2.4	<0.05	330	56	520	0.02	20
	7/24/79	20	6.75	8.95	1.0	1.2	<0.05	300	35	510	0.02	20
	7/31/79	18	7.10	9.10	1.1	2.4	<1.10	340	33	-	0.02	-
	8/15/79	18	6.70	9.25	0	0.8	0.07	340	32	565	0.02	2
	1/15/80	-	9.6	8.99	-	1.1	0.05	86	28	640	0.02	1
	2/5/80	-	5.8	8.93	-	1.4	0.05	364	26	580	0.02	25
	4/8/80	-	7.3	8.48	-	1.5	0.05	390	6	540	0.02	<1

TABLE 35 Water Quality Evaluations of Water Distribution System in Sioux Falls,
South Dakota (con't)

Sample Point	Date	Temp. °C	D.O. (mg/l)	pH	Chlorine Resid. Free (mg/l)	Chlorine Resid. Total (mg/l)	Total Iron (mg/l)	Hardness (mg/l as CaCO ₃)	Alkalinity (mg/l as CaCO ₃)	Spec. Cond.	Mn (mg/l)	SPC (no/ml)
J3	5/30/79	16	5.26	8.70	0.5	0.6	0.69	340	31	650	<0.02	10
	6/6/79	14	4.18	9.35	0.5	1.2	0.35	320	42	620	<0.02	2
	6/24/79	-	-	-	-	0	-	-	-	0	-	-
	6/19/79	12	-	9.55	0.3	0.8	0.25	320	46	490	<0.02	320
	6/31/79	14	4.70	9.55	0	0.5	0.38	360	44	620	<0.02	690
	7/11/79	16	6.09	9.30	0.5	1.0	0.27	320	60	460	0.02	250
	7/24/79	17	3.60	9.15	0.1	0.4	0.19	300	39	465	<0.02	30
	7/31/79	17	3.85	9.25	0.1	0.3	0.35	320	35	500	<0.02	-
	8/15/79	18	3.90	9.20	0	0.2	0.26	330	33	520	<0.02	35
	1/15/80	-	9.10	9.01	-	0	0.28	410	32	540	<0.02	3
	2/5/80	-	5.60	9.38	-	0.8	0.13	348	30	560	<0.02	15
	4/8/80	-	7.50	9.16	-	0.4	0.05	344	32	510	<0.02	NA
J4	5/30/79	13	3.91	9.06	0.1	0.4	0.32	340	32	670	<0.02	3
	6/6/79	15	3.27	9.20	0.1	0.6	1.25	310	35	600	0.03	<1
	6/13/79	16	3.60	9.05	0	0.4	0.32	320	50	670	<0.02	270
	6/19/79	15	-	9.15	0.2	0.6	0.33	320	37	510	<0.02	160
	6/27/79	16	4.27	9.40	0.1	0.4	0.20	330	47	610	<0.02	4
	7/11/79	17	3.30	9.25	0.2	0.6	0.52	350	57	540	<0.02	2
	7/24/79	18	4.90	9.25	0.2	0.7	0.13	300	44	475	<0.02	11
	7/31/79	18	3.40	9.35	0.1	0.4	0.46	360	33	510	0.02	-
	8/15/79	20	2.45	9.35	0	0.2	0.36	330	34	550	<0.02	1
	1/15/80	-	9.00	9.10	-	0.26	0.14	386	34	580	<0.02	5
	2/5/80	-	4.40	9.36	-	0.2	0.23	346	32	560	<0.02	3
	4/8/80	-	4.60	8.90	-	0.2	0.31	400	30	510	<0.02	44

TABLE 35 Water Quality Evaluations of Water Distribution System in Sioux Falls, South Dakota (con't)

Sample Point	Date	Temp °C	D.O. (mg/l)	pH	Chlorine Free (mg/l)	Chlorine Resid. Total (mg/l)	Total Iron (mg/l)	Hardness (mg/l as CaCO ₃)	Alkalinity (mg/l as CaCO ₃)	Spec. Cond.	Mn (mg/l)	SPC (no/ml)
J5	5/30/79	11	6.43	9.05	0.6	1.0	0.17	350	34	620	<0.02	8
	6/6/79	12	5.29	9.30	0.3	0.8	0.43	300	27	600	0.02	80
	6/13/79	14	4.30	9.10	0	1.0	0.10	310	49	660	<0.02	150
	6/19/79	14	-	9.45	NT	NT	0.15	320	51	540	<0.02	1200
	6/27/79	15	4.64	9.55	0	0.2	0.11	360	42	640	<0.02	590
	7/11/79	16	5.23	9.20	0.4	1.0	0.18	320	60	520	<0.02	10
	7/24/79	16.5	4.40	9.20	0.3	0.8	0.16	340	37	510	<0.02	14
	7/31/79	18	3.90	9.25	NT	NT	0.18	310	35	520	<0.02	-
	8/15/79	19	3.55	9.40	NT	NT	0.15	380	38	545	<0.02	180
	1/15/80	-	9.3	9.13	-	0.3	0.05	372	34	560	<0.02	36
	2/5/80	-	6.1	9.22	-	0.65	0.05	372	32	600	<0.02	1
	4/8/80	-	7.0	8.73	-	0.3	0.09	420	28	550	<0.02	3
J6	5/30/79	15	7.65	9.20	0.9	1.2	0.19	340	34	660	<0.02	17
	6/6/79	14	6.32	9.10	0.6	1.5	0.25	330	35	640	<0.02	2
	6/13/79	23	5.00	9.05	0.9	1.9	0.18	310	46	620	<0.02	33
	6/19/79	14	-	9.25	0.8	2.0	0.19	300	44	490	<0.02	13
	6/27/79	15	5.12	9.15	0.8	1.8	0.45	340	46	600	0.04	<1
	7/11/79	15	4.91	9.15	0.4	1.0	0.12	360	70	560	0.02	10
	7/24/79	17	4.70	9.05	0.6	1.2	0.08	300	44	515	<0.02	21
	7/31/79	19	4.90	9.10	0.4	0.9	0.12	320	32	610	<0.02	-
	8/15/79	18	4.95	9.35	0.5	0.7	0.20	370	34	560	<0.02	31
	1/15/80	-	9.30	8.81	-	0.75	0.08	408	30	580	<0.02	2
	2/5/80	-	6.20	9.15	-	0.70	0.13	376	30	590	<0.02	3
	4/8/80	-	6.50	9.66	-	0.70	<0.05	410	28	540	<0.02	3

previously deposited pipe sediments are causing the increase in iron concentrations. The dissolved oxygen concentration also declined as water migrated through the distribution system. This could be due to bacterial respiration or iron oxidation. The pH, hardness and alkalinity did not vary significantly in the distribution system.

In summary, the Sioux Falls data show that increases in iron concentrations and a concomitant depletion in dissolved oxygen occurred at several sampling points throughout the distribution system. Although high chlorine residuals reduced SPC values, there was no clearly evident relationship between chlorine residuals and SPC's.

FIRE HYDRANT FLUSHING SAMPLE ANALYSES

Sterilized sample bottles were mailed to the seventeen participating utilities throughout the U.S. These are the same utilities that agreed to cooperate in the National Field Studies for water quality deterioration in the water distribution systems. Only twelve utilities collected and returned the samples. The utilities were instructed to collect hydrant flushing samples in their water distribution system problem areas. The samples were to be collected in sterilized bottles after allowing the hydrant to flush for 60 seconds to remove stagnant water in the stem. The collected samples were mailed to University of Missouri-Columbia in a prepaid package. Soon after receipt in Columbia, samples were analyzed. On an average, the samples were about 6 days old when the analyses were performed. The chemical parameters analyzed were: pH, alkalinity, total iron, sulfate, sulfide, $\text{NH}_3\text{-N}$, total solids and total volatile solids.

For microbiological testing, six general enrichment media were for sulfur oxidizing bacteria, nitrogen-fixing bacteria, nitrifying bacteria, denitrifying bacteria, sulfate-reducing bacteria and iron-precipitating bacteria. Two ml of water samples were added to duplicate enrichment culture tubes and incubated at room temperature. For anaerobic organism growth (denitrifying and sulfate-reducing), screw capped tubes were filled to the top with media and sample. Bacterial enumeration of various species was done by plating duplicate 1 ml. and 0.1 ml. samples in the above solid media except for the anaerobic organisms. Diluted Standard Plate Count (SPC) media (diluted 2-fold) and R-2A media (EPA recommended) were used to enumerate the total bacterial concentrations in the samples.

Results of the bacterial and chemical analyses of the hydrant flushing samples are given in Table 36 and 37, respectively.

TABLE 36
Bacteriological Analyses of Hydrant Flushing Samples

Utility	Sulfur Oxidizing	Nitrogen Fixing	Nitrifying	Denitrifying	Sulfate Reducing	Iron Precipitating	R-2A	2x Diluted SPC
Crete, Nebraska	++ 402/ml	++ 152/ml	++ <1/ml	++	-+	++ 3/ml	198/ml	957/ml
Wichita, Kansas	+- <1/ml	+- <1/ml	--	--	--	--	<1/ml	1/ml
Columbia, Missouri	+- <1/ml	+- <1/ml	++ <1/ml	--	--	--	1/ml	<1/ml
Elmira, New York	++ <1/ml	+- 4/ml	++ <1/ml	NM	--	++ <1/ml	4960/ml	5330/ml
Champaign, Illinois	++ 177/ml	++ 290/ml	++ 2/ml	NM	--	++ <1/ml	TNTC (>10,000/ml)	TNTC (>10,000/ml)
Durham, N. Carolina	--	--	--	--	--	--	<1/ml	<1/ml
Minneapolis, Minnesota	--	--	--	--	--	--	2/ml	2/ml
Tampa, Florida	--	--	--	--	--	--	<1/ml	<1/ml
Tacoma, Washington	++ 434/ml	++ 290/ml	++ <1/ml	++	++	++ <1/ml	973/ml	8400/ml
Sioux Falls, South Dakota	++ 1/ml	++ 1/ml	-- <1/ml	--	++	+- <1/ml	30/ml	12/ml
Chicago, Illinois	++ 260/ml	++ 5680/ml	++ <1/ml	++	--	--	5010/ml	24,450/ml
Portland, Maine	++ TNTC	++ TNTC	++ 60/ml	++	++	++ 5/ml	TNTC (>10,000/ml)	TNTC (>10,000/ml)

TABLE 37
Chemical Analyses of Hydrant Flushing Samples

Utility	pH	Alkalinity mg/l as CaCO ₃	Total Fe mg/l	Sulfate mg/l	Sulfide mg/l	Ammonia mg/l as N	Total Solids mg/l	Total Volatile Solids mg/l	Appearance of Water Sample
Crete, Nebraska	7.95	229.0	9.15	42.0	0.0	0.0	360.0	12.0	Slightly turbid
Wichita, Kansas	8.05	95.0	0.18	69.0	0.0	0.278	392.0	18.0	Clear
Columbia, Missouri	8.60	133.0	0.26	63.0	0.0	0.0	300.0	26.0	Clear
Elmira, New York	8.78	158.0	30.0	49.0	0.0	0.018	430.0	66.0	Very turbid, brown
Champaign, Illinois	8.10	113.0	0.33	43.0	0.0	0.88	176.0	34.0	Clear
Durham, North Carolina	6.80	12.0	3.90	31.0	0.0	0.0	56.0	0.0	Slightly turbid
Minneapolis, Minnesota	7.75	54.0	0.04	27.0	0.0	0.51	110.0	8.0	Clear
Tampa, Florida	7.67	141.0	0.04	17.0	0.0	0.0	220.0	34.0	Clear
Tacoma, Washington	7.31	84.0	0.40	NM	0.0	0.0	200.0	82.0	Clear
Sioux Falls, South Dakota	8.32	34.0	0.59	NM	0.03	NM	642.0	94.0	Very turbid, brown
Chicago, Illinois	6.80	113.6	0.416	NM	0.08	0.0	NM	NM	Slightly turbid
Portland, Maine	-	6.8	141.66	NM	0.58	0.0	NM	NM	Very turbid, brown

The following observations can be made on the bacteriological analyses results; The three samples that gave negative results for all six enrichment culture media contained very few organisms in SPC and R-2A plates. These samples had comparatively low turbidity and were low in total and volatile solids. Samples which were turbid and brown in color showed positive results for most of the enrichment culture tests. They also had a high concentration of total solids and total iron. The solids appeared to be corrosion products flushed from the pipes during sampling. The standard plate counts of these samples varied widely, from 12/ml to 10,000/ml. The sulfate-reducing organisms were generally present in samples containing all other organisms, except in the case of Sioux Falls, South Dakota. From the limited data obtained it appears that hydrant flushing samples may contain considerable numbers of microorganisms. Moreover, the quality of samples containing large amounts of microorganisms was generally poor.

In most of the samples analyzed, the diluted SPC media developed more colony growth compared to R-2A media.

Some of the samples had high iron (Portland, Me., Elmira, N.Y. and Crete, Ne.) indicating main corrosion problems. One sample had a relatively high sulfide concentration (Portland, Me.) which indicated reducing conditions in the main. The presence of sulfate-reducing bacteria in this sample provided a clue as to the presence of sulfides in the sample. Generally, only a fraction of the total solids in the hydrant flushing samples were volatile (0 to 19%) except for one sample (Tacoma, Wa.) where this percent volatile ranged up to 41%.

SECTION 5

MANIFOLD STUDIES

INTRODUCTION

A pipe manifold system was fabricated to study water quality changes and microbiological growths in distribution systems in the laboratory. This manifold system facilitated simulation of the conditions in a water distribution system. These manifold systems were used in several studies to answer the following questions:

1. What levels of total organic carbon (TOC) stimulate microbial growth?
2. What disinfectant levels (free and combined chlorine) control microbial growth?
3. Does dissolved methane promote microbial growth?
4. Do phosphate formulations used for corrosion control promote microbial growth?
5. What water quality changes occur with time using waters of different qualities?
6. Do different pipe materials have different potentials for attached microbial growths?

Materials and Methods

A. Experimental Plan and Apparatus

Figure 20 shows the overall schematic sectional profile of the laboratory pipe manifold system. It consisted of six removable plastic tubes attached to a manifold system. Water from the University of Missouri-Columbia Civil Engineering Hydraulic Laboratory tap water supply was introduced into a constant head inlet reservoir. Nutrients for microbial growth, such as organic substrates and inorganic salts, were fed to the reservoir using metering pumps. A mechanical device was employed to mix the constituents in the reservoir. At a flow rate which varied from 110 to 220 ml/minute, the

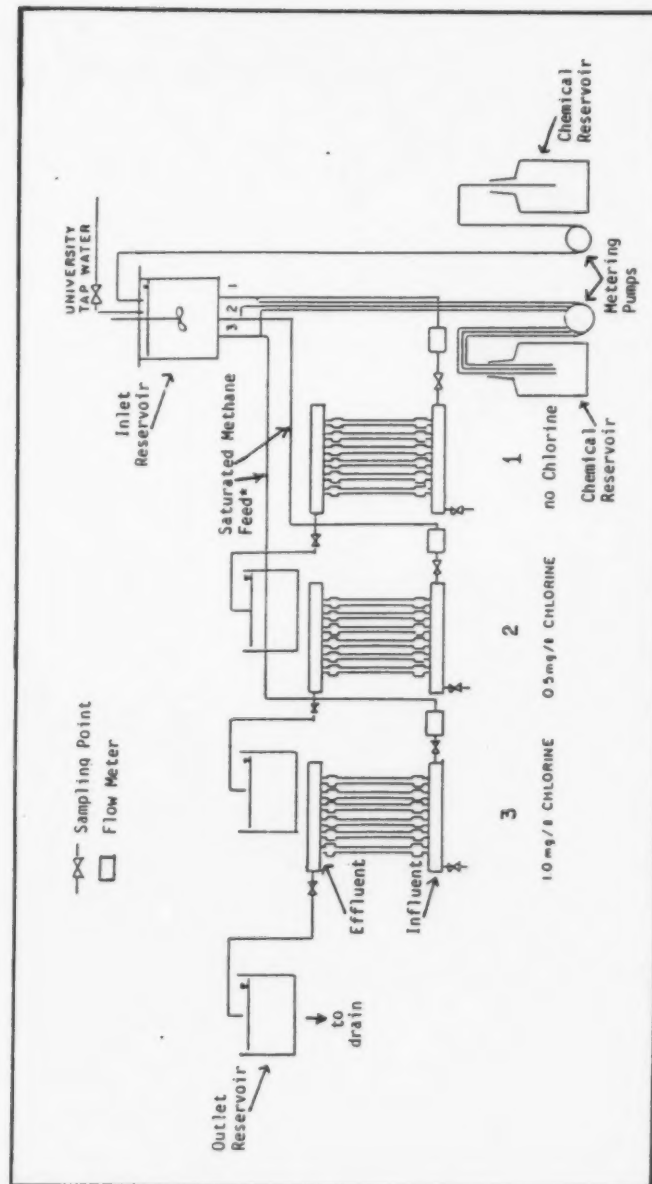


Fig. 20 Schematic Diagram of Laboratory Pipe Manifold Systems

solution was then introduced into three independent mixing tanks where three different doses of free chlorine (0.1, 0.5, 1.0 mg/l) were maintained using metering pumps.

The chlorinated water was introduced into three separate pipe manifold systems with individual feed lines. The pipe manifold experiments were continued after correction of some initial flow distribution problems as indicated by a dye test. Placement of 2 mm diameter orifices in the outlet end of the manifold tubes established a more uniform flow distribution through the six tubes. An outlet reservoir was also provided to facilitate the flow control and ensure a full flow in the system.

For the experiments designed to study the effects of methane, compressed methane gas was introduced into a 1.5 meter column saturator. This methane-saturated water was mixed with the feed water to vary methane concentrations.

B. Analytical Methods

The flow of water through the pipe manifold over a period of time eventually caused the growth of microbes and the accumulation of sediments on the walls of the removable clear plastic pipe. Weekly, one of the manifold pipes was removed and a clean substitute was put in its place. The accumulation of biological growth and sediments on the pipe walls were removed using a sterile rubber squeeze-type plunger. The organic and mineral matter in the slime layer removed was resuspended in 200 ml of sterile distilled water. Samples from this suspension were taken for the analysis of standard plate counts, total and volatile, dissolved and suspended solids. These data indicated the amount of microbiological and inert mass associated with the accumulations on the manifold pipes at different times. Finally, data were obtained to show the changes in the accumulations resulting from maintaining of different chlorine doses in each pipe manifold system.

Water quality measurements were also made weekly on the tap water, influent, effluent and at intermediate points in the pipe manifold. Sampling points are shown in Figure 20. Analyses, conducted according to Standard Methods, (95) included pH, alkalinity, temperature, free and total chlorine, total and volatile residue, total iron, dissolved oxygen, standard plate count, sulfate, hydrogen sulfide, ammonium ion and turbidity.

Total organic carbon (TOC) was analyzed using a Beckman Total Organic Carbon Analyzer equipped with an Infrared Analyzer and recorder. Samples were acidified with (0.1+1) HCl,

purged with nitrogen gas for 10 minutes to remove any inorganic carbon present and injected with a 20 μ l syringe. In later experiments, a highly sensitive Dohrmann TOC Analyzer was used. For methane analysis, samples were taken at the inlet, outlet and a dead end in each manifold as well as from the constant head reservoir. A sample was also taken from the saturator. Samples were collected in 16x125 mm screw cap test tubes. All samples were about 18 ml, except the methane saturator sample, which was 50 ml and was collected in a fritted joint collection bottle. The tubes were filled to capacity and then allowed to overflow at least one tube volume. Caps were filled with the sample water and quickly screwed onto the tubes to exclude all gas bubbles.

Standard solutions of various methane concentrations were made by diluting a water sample taken from the methane saturator. Dilutions used were 1:0, 3:1, 1:1, 1:3 and 0:1 (sample:diluent), yielding concentrations of 1.0, 0.75, 0.50, 0.25 and 0.0 times that of the saturated concentrations determined by Novane and Fenninger (98) and reported in Table 38. All samples and standards were refrigerated until analysis was performed. All analyses are performed within 3 hours of the sampling time.

Methane analysis was performed using a Bendix 2500 Gas Chromatograph. This instrument was equipped with a flame ionization detector and a Bendix electrometer.

The column chosen was a 1.8 meter by 4 mm glass column which was not coiled. It was packed with Supelco 45/60 mesh, 5A molecular sieve material. The first 300 mm section was utilized as a water-absorbing precolumn and was packed with 8 mesh dessicant (CaSO_4), which was crushed to fit the column.

The column was activated by heating to 250 $^{\circ}$ C for 24 hours. The oven temperature was then lowered to 60 $^{\circ}$ C at which time inlet and detector temperatures were stabilized to 210 $^{\circ}$ C and 235 $^{\circ}$ C, respectively.

Nitrogen was used as the carrier gas at a flow of 42.4 l/min. Hydrogen was used as the detector gas with oxygen serving as the oxidant.

Standards were injected to determine the system detention time, which was found to be excessive at 60 $^{\circ}$ C. The oven temperature was increased to 70 $^{\circ}$ C which provided an optimum working time and yielded accepted peak heights at low attenuation and minimum noise.

Output was recorded on a chart recorder at a speed of 75 cm/hr.

TABLE 38

SATURATED METHANE CONCENTRATIONS IN WATER AT VARIOUS TEMPERATURES
(After Novane, et al., (98))

Temp., °C	Methane Saturation Concentration, mg/l CH ₄
20	23.2
21	22.7
22	22.2
23	21.8
24	21.3
25	20.9
26	20.5
27	20.1
28	19.7
29	19.4
30	19.0

Methane peaks were identified using Scott-analysed gases. Two types were utilized. The first was a combination of low alkanes which had a methane concentration of 18 ppm (by volume) and the second was methane in air at 9.6 ppm (by volume). These gases revealed methane peaks having a detention time of two minutes.

Standard solutions were run and found to be linear when peak height was plotted against methane concentration.

The samples were then tested. Injection of 5 μ l was performed using a Hamilton microliter syringe. The syringe was flushed with acetone after duplicates of each sample were injected.

Electrometer attenuation was held at 20, which provided good peak heights for both the standards and the samples when used with the chosen sample size. At lower attenuation, the noise became excessive and, at higher levels, the peaks of the lower methane concentrations became hard to distinguish from each other.

After 25 sample injections, it was necessary to replace the injection port septum to provide accurate results.

C. Composition of Influent Water

The feed water employed was University of Missouri-Columbia tap water. This water was supplied by four wells located on campus. The major well is located approximately 275 meters from the Civil Engineering laboratories. Treatment of this ground water is limited to the addition of some chlorine. Table 39 summarizes the average analysis of this feed water.

In the experiments dealing with microbiological growth at various TOC levels and its suppression at various disinfectant levels, the inlet feed to the manifold systems included various amounts of substrates and nutrients. Initially, three TOC substrate levels were studied (0, 5 mg/l and 10 mg/l carbon). Glucose was the carbon source with supplemental amounts of ammonium chloride and sodium phosphate added as the nutrient sources.

Sodium hypochlorite was the growth-suppressing disinfectant used in the initial study. The addition of organic substrate, nutrients and chemicals were conducted according to the schedule for different experiments shown in Table 40.

In experiments employing the saturated methane feed system, the average methane concentrations in the three experiments were 0.0 mg/l, 8.9 mg/l and 13.3 mg/l.

TABLE 39
UMC CIVIL ENGINEERING HYDRAULIC LABORATORY AVERAGE WATER QUALITY

pH	7.6
TDS	326 mg/l
Hardness	252 mg/l as CaCO_3 eq
Alkalinity	244 mg/l as CaCO_3 eq
$\text{SO}_4^{=}$	32 mg/l
H_2S	0.03 mg/l
Total Iron	0.06 mg/l

TABLE 40
INLET FEED COMPOSITION FOR THE MANIFOLD EXPERIMENT INVOLVING
MICROBIAL GROWTH INHIBITION BY CHLORINE

Experiment Number	TOC mg/l as C	NH ₄ ⁺ mg/l as N	Phosphate, mg/l as P	Chlorine, mg/l as Cl
1	10	0.5	0.1	0.0
2	10	0.5	0.1	0.5
3	10	0.5	0.1	1.0
4	5	0.5	0.1	0.0
5	5	0.5	0.1	0.5
6	5	0.5	0.1	1.0
7	0	0.5	0.1	0.0
8	0	0.5	0.1	0.5
9	0	0.5	0.1	1.0

Results and Discussions

A. Growth Inhibition by Chlorine

The results of chlorine addition on the microbial growth on the removable manifold tubes are presented in Figure 21. The total solids measured in this experiment represent the amount of microbial growth occurring on the tubes due to the presence of nutrients in the feed water.

In spite of continual chlorination, analysis of the accumulated solids showed increases in biological growth with time (Figure 21). With the addition of 0.5 mg/l chlorine, 80 - 100% of the available chlorine was in the form of a chloramine residual. Perhaps for this reason, 0.5 mg/l chlorination did not result in growth inhibition. However, the addition of 1.0 mg/l of chlorine resulted in marked growth suppression. In addition, the decrease of TOC concentration from 10 mg/l to 5 mg/l also reduced the attached growth markedly. The volatile solids data for this experiment exhibited the same pattern as the total solids data shown in Figure 22. Water quality data (other than total and volatile solids) for one typical experiment is shown in Table 41.

Decreases in the hypochlorous acid residuals and dissolved oxygen concentrations were consistently observed in the effluents from the manifolds. Moreover, the production of hydrogen sulfide was indicated in the test systems with 0 and 0.5 mg/l chlorine additions. Microbiological analysis confirmed the presence of sulfate-reducing organisms. Other heterotrophic organisms isolated were iron-precipitating organisms, pigmented Gram-negative rods, and sulfur-oxidizing organisms. Due to the source of carbon (glucose) that was added to the system, slimy and cottony textured bioflocculation was noted in the manifold system.

B. Methane Stimulation Studies

Figure 23 shows the changes in the SPC of the resuspended biological growth removed from the manifold tubes. There was a substantial increase in the number of microorganisms found in the system where methane was fed as compared to the control. Water quality changes monitored for the manifold inlet and outlet samples indicated clearly that dissolved methane was being depleted, presumably by microbial action. Some oxygen depletion was also observed in the manifold system.

Figure 24 shows the variations of suspended solids accumulation in the manifold tubes at various methane doses. The difference in magnitude of biological growth as measured by suspended solids was not as significant for different methane levels as were difference observed with standard plate count determinations. However, the pattern of growth

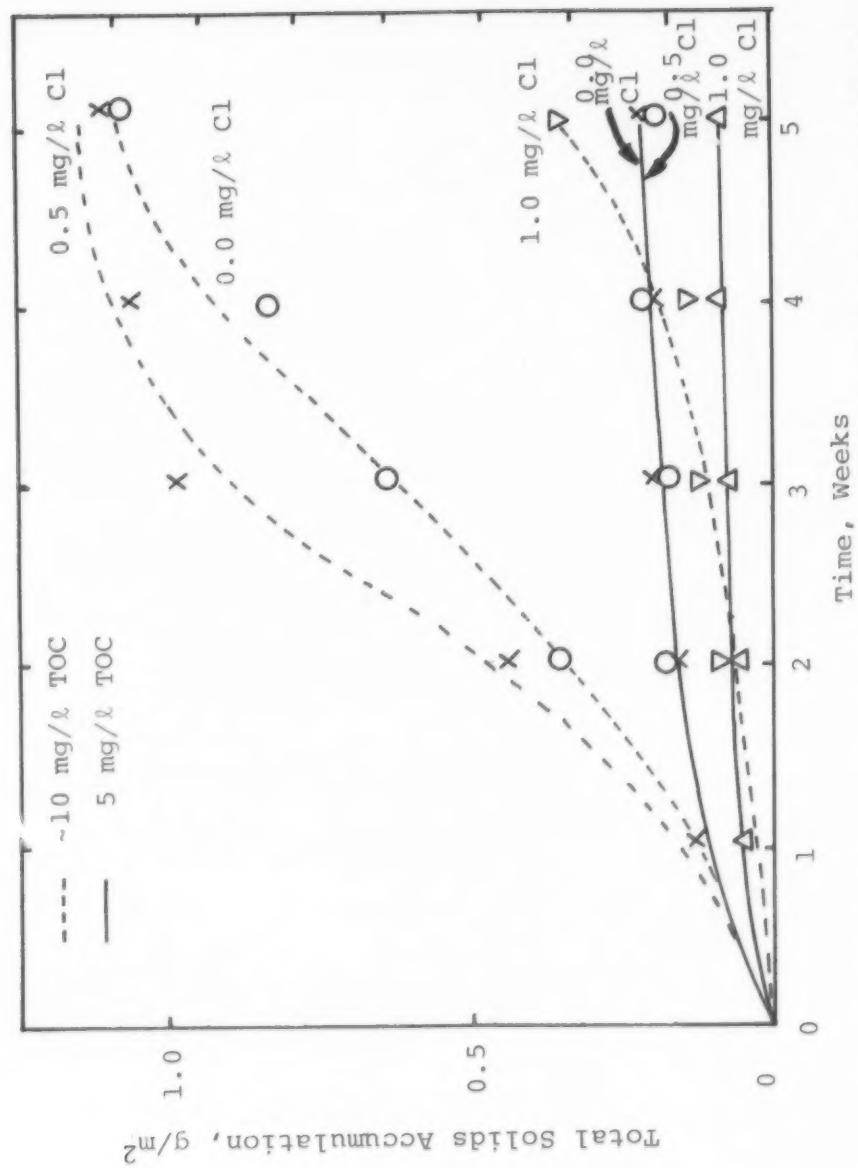


Fig. 21 Total Solids Accumulation in Manifold Tubes Versus Chlorine Dose

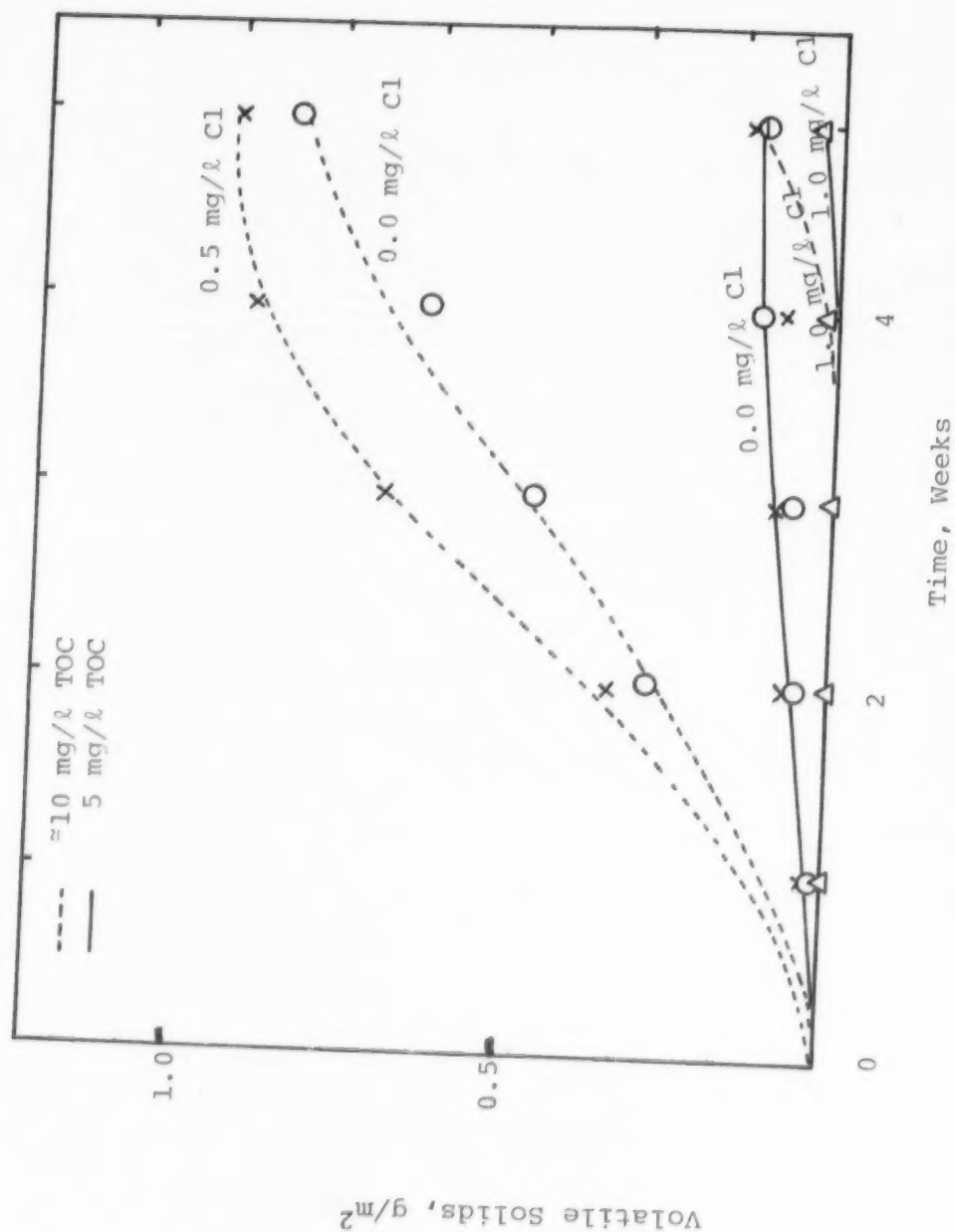


Fig. 22 Changes in Volatile Solids Accumulation in Manifold Tubes Versus Chlorine Doses

TABLE 41

WATER QUALITY DATA OF INFLUENT & EFFLUENT TO THE MANIFOLD II
(Doses: TOC-10 mg/l; NH_4^+ -0.5 mg/l; Phosphate-0.1 mg/l; Chlorine-0.5 mg/l)

Sample	pH	Alka- linity mg/l as CaCO_3 eq	HOCl mg/l as Cl	Total Chlorine mg/l as Cl	Sulfides mg/l as H_2S	Sulfates mg/l as $\text{SO}_4^{=}$	Total Fe mg/l	TOC mg/l as C	NH_4^+ mg/l as N	D0 mg/l	SPC #/ml
Manifold II Influent	7.7	238	0.10	0.40	0.013	34	0.039	12.8	0.2	6.9	1.2×10^5
	7.8	NM	0	0.30	0.01	35	NM	8.6	0.3	6.2	1.9×10^5
	7.3	220	0.10	0.10	0.055	37	0.043	9.3	0.5	1.3	1.0×10^7
Manifold II Effluent	7.7	240	0.05	0.50	0.034	34	0.033	11.5	0	5.3	3.8×10^5
	7.7	NM	0	0	0.04	35	NM	7.8	0.1	5.0	2.4×10^5
	7.3	214	0	0	0.17	36	0.038	10.9	0.4	0	2.0×10^7

NM: Not Measured

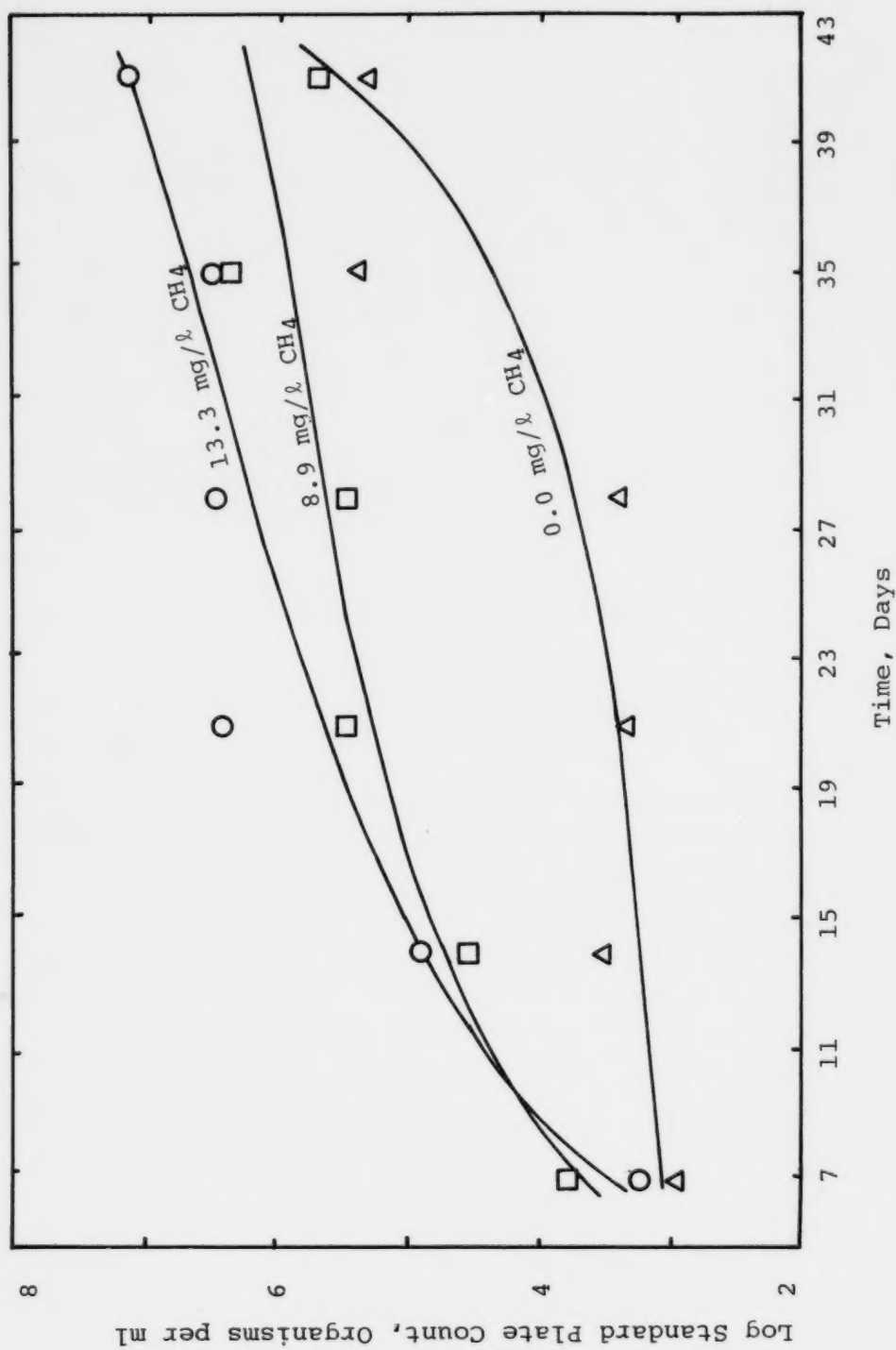


Fig. 23 Biological Growth in Manifold Tubes at Various Methane Doses

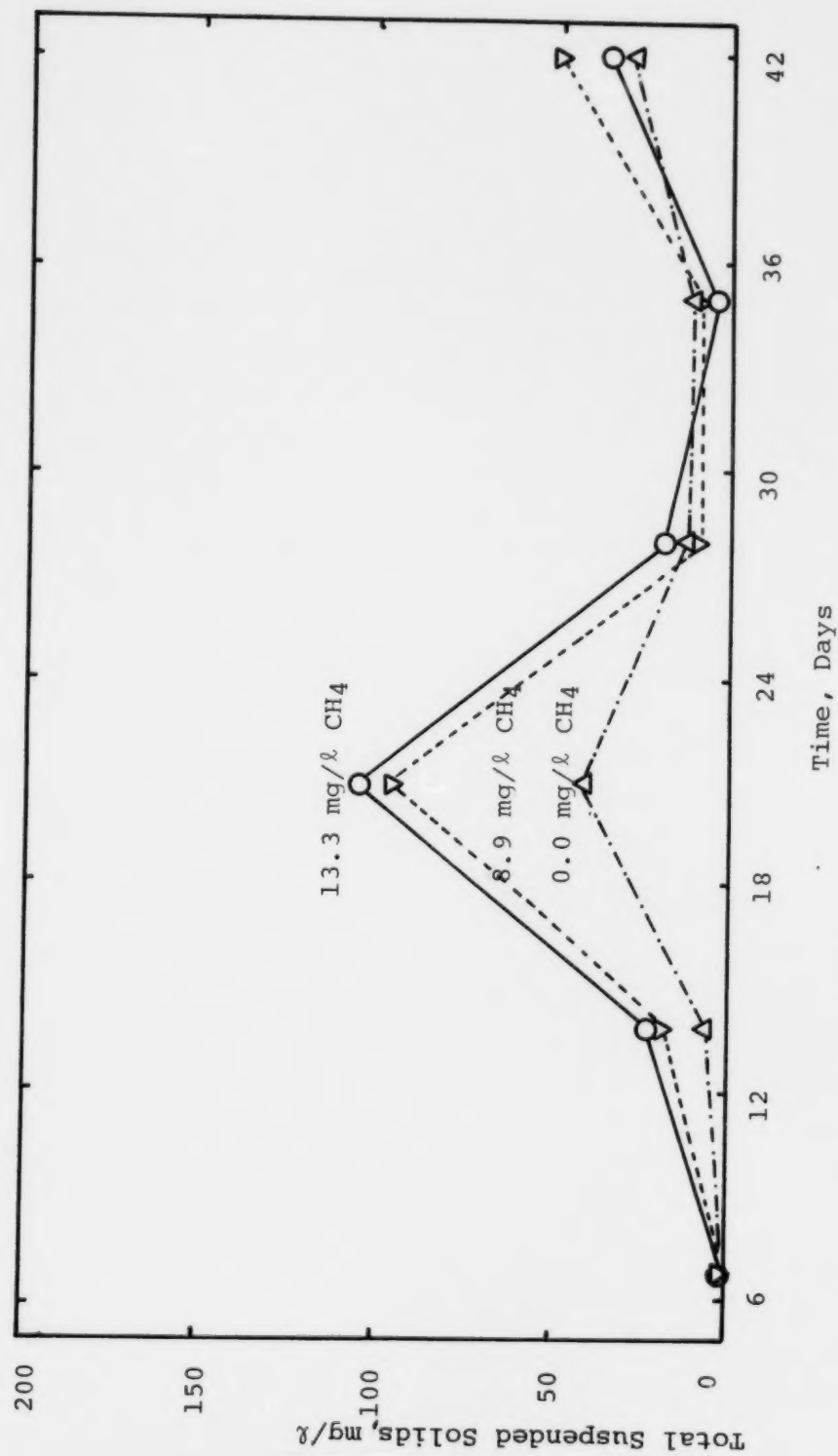


Fig. 24 Suspended Solids Accumulation in Manifold Tubes Versus Methane Dose

was similar. The reason the decreased growth after 21 days operation was not clear unless some sloughing of the attached growth had begun.

The results of this experiment clearly show that methane found in ground waters could serve as a substrate for microbial growth in water distribution systems. Thus, in turn, could contribute to quality deterioration of the supplied water.

C. Pipe Manifold Studies Using Different Pipe Materials

In order to determine the effect of pipe material on the biological growth in pipes, three laboratory manifold systems consisting of removable pipe sections of three different pipe material (PVC (polyvinylchloride), copper and steel) were fabricated. Figure 25 shows the schematic of the system. The experimental format for these manifolds was similar to that described for the manifold system used in earlier experiments.

Water quality data for the influent tap water and effluent of the manifolds were measured. Table 42 shows the water quality of the influent and effluent water for the PVC manifold. The effluent water quality of the copper and steel manifolds were very similar to that of the PVC system. As the figures show, there was no noticeable change in the quality of the effluent of the manifolds compared to the influent, except for increases in SPC. Figure 26 shows the changes in microorganism concentrations in the pipe manifold influent and effluent samples.

Table 43 tabulates the results of the analysis of sediments removed from the PVC, copper and steel pipe sections. It can be seen from these results that the steel pipe sections accumulated the most sediments, while copper and PVC accumulated only small amounts of sediment over the 35 day test period. The data show that, in general, the sediment accumulation increased with time. The SPC data expressed as number of microorganisms/cm² of the pipe's inner surface shows that there was a large number of microorganisms in these sediments, even in the PVC pipe (10⁴/cm²), where the total mass of sediments was lowest. These results are shown in Figure 27.

Microorganism concentrations in the effluent samples of all three manifold systems increased over the influent sample, indicating some growth of these organisms, despite inordinately low TOC concentrations ranging from 0.3 - 0.5 mg/l.

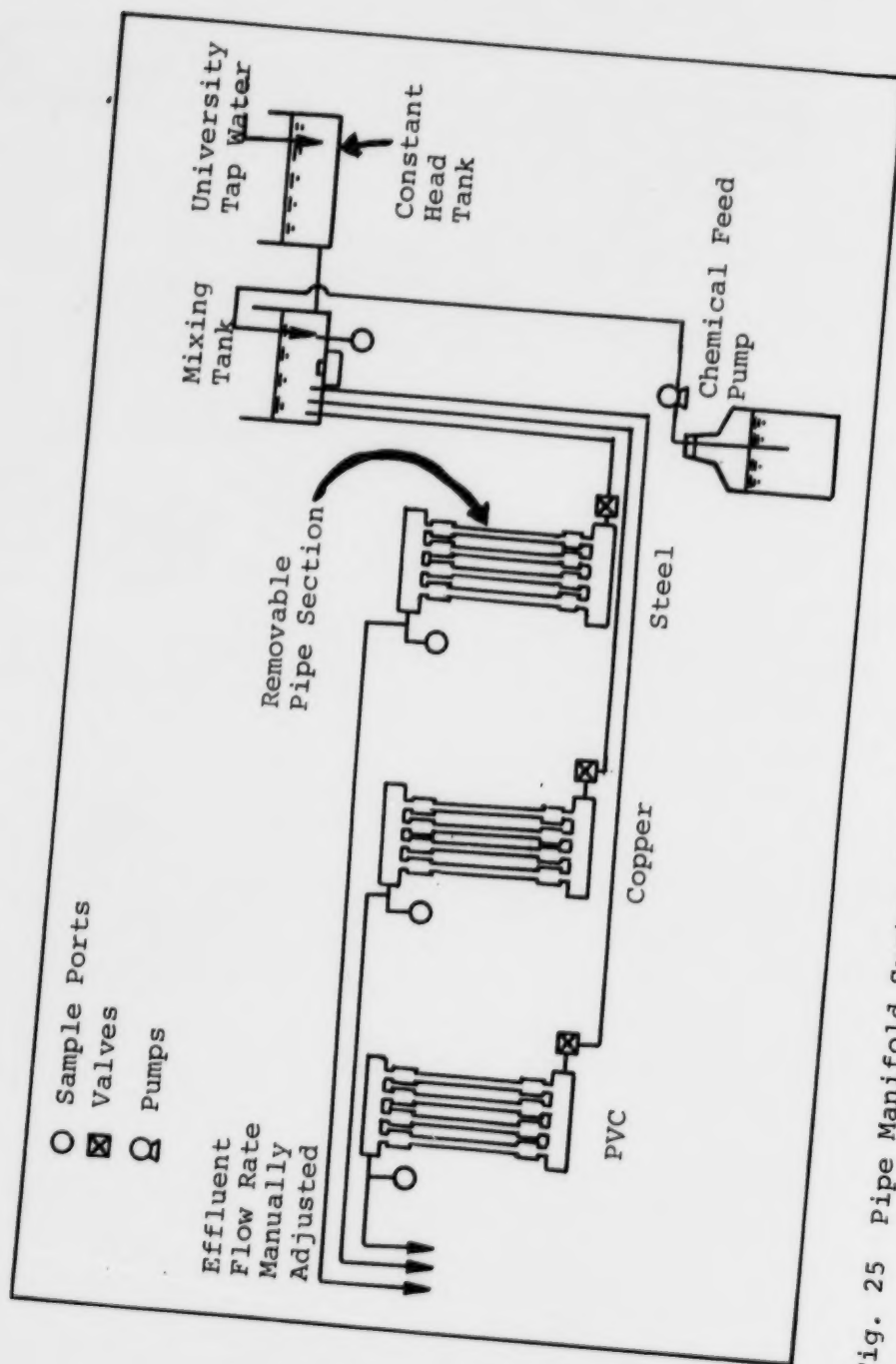


Fig. 25 Pipe Manifold System Schematic

TABLE 42
MANIFOLD TAP WATER INFLUENT AND PVC MANIFOLD EFFLUENT QUALITY

<u>Tap Water Influent Quality</u>							
Elapsed Time, Days	Temp. °C	D.O. mg/l	pH	Alkalinity mg/l as CaCO ₃ eq	Total Iron mg/l	SPC #/ml	TOC mg/l
2	22	8.60	7.91	264	0.05	9.2x10 ¹	NM*
4	23	9.00	7.80	240	0.05	2.7x10 ²	0.469
7	22	9.10	7.82	252	0.02	5.0x10 ²	NM
11	22	9.60	7.95	260	0.05	5.6x10 ²	NM
14	22	8.90	7.95	250	0	2.1x10 ²	NM
18	22	9.15	7.93	248	0.01	1.5x10 ²	0.361
21	24	8.60	7.92	250	0.01	4.6x10 ²	NM
32	22	8.90	8.13	242	0.03	1.5x10 ²	NM
35	22	9.05	7.91	244	0.03	1.4x10 ²	0.446

<u>PVC Manifold Effluent Quality</u>							
2		8.95	7.91	260	0.067	2.4x10	-
4		9.00	7.80	242	0.06	1.1x10 ³	0.313
7		9.10	7.82	246	0.02	1.1x10 ⁴	-
11		9.30	7.80	250	0.05	3.6x10 ³	-
14		8.70	7.92	242	0	7.6x10 ²	-
18		9.20	8.03	242	0.01	1.1x10 ³	0.470
21		8.45	7.91	248	0.01	9.2x10 ²	-
32		8.80	8.10	240	0.03	7.6x10 ²	-
35		8.95	7.85	244	0.03	1.3x10 ³	0.612

*NM = Not Measured

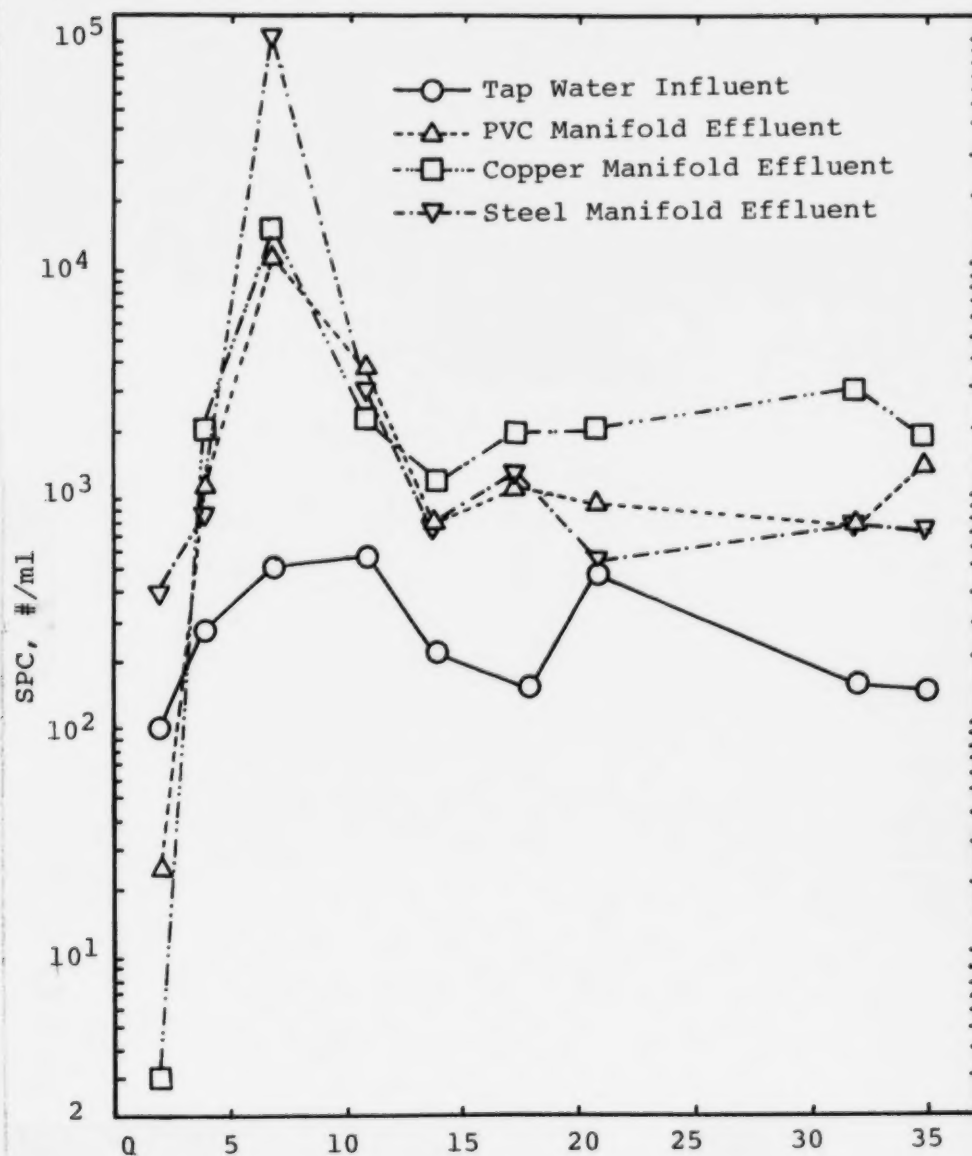


Fig. 26 Microorganisms in Tap Water Influent and PVC, Copper and Steel Pipe Manifold Effluents

TABLE 43
MANIFOLD PIPE SEDIMENT ANALYSIS

Manifold	Elapsed Time, Days	Total Residue mg/cm ²	Total Volatile Residue mg/cm ²	Total Non-Filterable Residue mg/cm ²	Total Non-Filterable Volatile Residue, mg/cm ²	SPC #/cm ²
PVC	7	0.019	trace	trace	trace	1.1x10 ⁴
	14	0.013	trace	0.025	trace	1.0x10 ⁴
	21	trace	trace	0.057	trace	9.5x10 ³
	35	0.076	0.017	0.008	trace	2.3x10 ⁴
Cu	7	0.064	trace	0.048	trace	1.4x10 ⁴
	14	0.052	0.048	0.079	trace	6.5x10 ⁴
	21	0.058	0.054	0.078	0.023	9.4x10 ⁴
	35	0.316	0.040	0.200	0.004	2.4x10 ⁷
Steel	7	1.110	0.102	1.300	0.138	1.1x10 ⁵
	14	2.697	0.286	2.347	0.238	1.0x10 ⁵
	21	5.952	0.587	2.960	0.296	3.0x10 ⁵
	35	5.621	0.454	4.367	0.434	2.6x10 ⁷

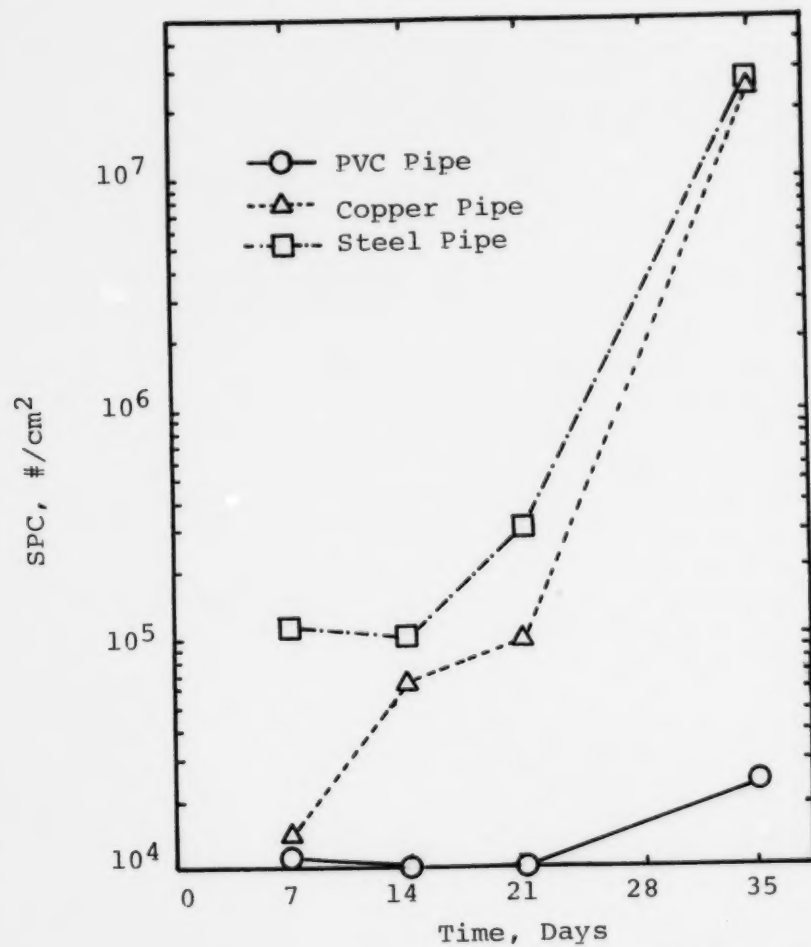


Fig. 27 Microorganisms in Sediments Removed from PVC, Copper and Steel Pipe Sections

In subsequent experiments the influent was treated with chlorine to form a hypochlorous acid residual and monochloramine, respectively. The intent of these experiments was to investigate the suppression of microbial growth by these disinfectants. The concentration of the chlorine and monochloramine were measured daily. The concentration was maintained between 1 and 2 mg/l as chlorine. The sediments from the pipe sections were collected at the end of 1, 2, 3 and 4 weeks.

Tables 44 and 45 show the water quality of the influent and effluents of the PVC manifold system for the experiments with chlorine and monochloramine, respectively. The effluent water quality for the steel and copper manifold systems was quite similar to the PVC manifold. The results show that D.O., pH, alkalinity and total iron did not change significantly with time. The data of Table 44 show the SPC remained quite low indicating that the hypochlorous acid residual was highly effective in controlling microorganisms in the manifold effluents. As shown in Table 45, chloramine at comparable concentrations, was not as effective as hypochlorous acid in controlling the microorganisms in the manifold effluents.

Table 46 shows the results of the analysis of sediments from the manifold pipe sections. The data again shows that the steel pipe sections accumulated most sediments compared to PVC and copper pipes.

It can be seen from Tables 43 and 46 that the chlorinated water creates more sediments than either the chloraminated or unchlorinated water. An important result of the analysis of the sediments for SPC is the indication that neither chlorine nor chloramine prevented microorganisms from accumulating within the materials attached to the pipe surfaces. This result may be of special importance to an understanding of how microbial processes can proceed in water mains even where low bacterial counts and disinfectant residuals are observed in samples of the bulk water.

D. Effect of Polyphosphate, Chlorine and Chloramine on Biological Growth in Manifold Systems

In these experiments the steel pipe manifold system described earlier was modified in order to determine the effects of influent water treatment on sediment deposition in the removable pipe sections and on cast iron test specimen corrosion rate. Clear plastic tanks designed to hold cast iron test specimens were connected to the manifolds in parallel. Figure 28 shows the modified manifold system.

TABLE 44
EFFECT OF CHLORINE ON PIPE MANIFOLDS WATER QUALITY

<u>Tap Water Influent Quality</u>							
Elapsed Time, Days	D.O. mg/l	pH	Alkalinity mg/l CaCO ₃ eq	Total Iron mg/l	Chlorine, mg/l		SPC #/ml
					Free	Combined	
1	8.9	7.7	242	0	2.15	0.05	3
4	9.2	7.7	244	0	1.50	0	<1
7	7.9	7.5	242	0.016	1.00	0.05	<1
11	9.1	7.8	250	0.01	1.65	0.1	<1
14	9.5	7.75	250	0.05	1.80	0.1	4
18	8.5	7.7	245	0.016	2.05	0.1	<1
21	9.5	7.7	248	0.016	0.90	0.1	10
25	9.5	7.8	246	0	1.70	0.05	3
28	10.2	7.7	244	0.03	0.95	0.05	8

<u>PVC Manifold Effluent Quality</u>							
1	8.95	7.5	252	0	1.9	0.15	5
4	9.2	7.6	238	0	1.3	-	<1
7	7.6	7.6	254	0.016	1.3	0.05	<1
11	9.1	7.7	250	0.01	1.9	0.1	40
14	9.2	7.7	248	0.05	2.05	0.1	2
18	8.6	7.75	239	0.016	2.2	0.05	<1
21	9.6	7.6	248	0.016	0.9	0.05	6
25	9.3	7.7	244	0	1.7	0.1	6
28	9.8	7.6	252	0.03	0.95	0.05	5

TABLE 45
EFFECT OF MONOCHLORAMINE ON WATER QUALITY OF PIPE MANIFOLDS

Tap Water Influent Quality								
Elapsed Time, Days	D.O. mg/l	pH	Alkalinity mg/l CaCO ₃ eq	Total Iron, mg/l	Free Chlorine, mg/l	Chloramine		SPC #/ml
						Mono	Di	
1	8.1	7.65	250	0.03	0	0.95	0.05	5.25x10 ²
4	9.0	7.75	240	0.02	0.10	1.40	0.20	7.5x10 ¹
7	9.9	7.70	250	0.03	0	2.05	0.20	7.4x10 ¹
11	9.0	7.80	244	0.02	0.01	2.20	0.15	9.0
14	9.2	7.75	244	0.01	0.01	1.05	0.30	1.1x10 ¹
18	8.6	7.80	240	0.02	0.10	2.05	0.15	8.0
21	9.5	7.80	248	0.01	0.05	1.35	0.25	7.3x10 ¹
28	9.3	7.85	246	0.01	0.05	1.70	0.35	1.5x10 ¹

<u>PVC Manifold Effluent Quality</u>								
1	8.0	7.70	244	0.03	0	1.15	0.10	1.72x10 ²
4	9.0	7.65	238	0.02	0.20	1.40	0.15	5.4x10 ¹
7	10.0	7.75	240	0	0	1.90	0.20	1.26x10 ²
11	8.9	7.85	244	0	0.05	2.20	0.20	4.0x10
14	9.2	7.80	246	0.01	0.05	1.00	0.30	5.5x10 ²
18	8.6	7.80	244	0.02	0.10	2.05	0.15	6.4x10 ¹
21	9.6	7.80	240	0.01	0.05	1.30	0.30	1.80x10 ³
28	9.2	7.75	244	0	0.05	1.70	0.30	2.5x10 ²

Table 46 Effect of Chlorine and Chloramine on Sediment Deposition in Pipe Manifolds

Sediment Analyses-Chlorine Addition

Manifold System	Elapsed Time, Days	Total Residue mg/cm ²	Total Volatile Residue mg/cm ²	Non-Filterable Residue mg/cm ²	Non-Filterable Volatile Residue mg/cm ²	Microorganism Concentration #/cm ²
PVC	7	7.78x10 ⁻¹	1.01x10 ⁻¹	trace	trace	2.47x10 ³
	14	8.13x10 ⁻¹	1.29x10 ⁻¹	2.85x10 ⁻¹	8x10 ⁻³	5.10x10 ³
	21	1.06	1.48x10 ⁻¹	trace	trace	9.47x10 ³
	28	3.14	4.66x10 ⁻¹	trace	trace	1.90x10 ³
Cu	7	1.02	1.35x10 ⁻¹	8.23x10 ⁻¹	7.48x10 ⁻³	6.08x10 ³
	14	8.1x10 ⁻¹	1.25x10 ⁻¹	1.25x10 ⁻¹	2.06x10 ⁻²	2.55x10 ³
	21	2.73	3.12x10 ⁻¹	5.43x10 ⁻¹	2.05x10 ⁻²	5.89x10 ³
	28	2.77	2.75x10 ⁻¹	8.05x10 ⁻¹	9.40x10 ⁻³	1.87x10 ³
Steel	7	2.43	1.53x10 ⁻¹	1.25	1.43x10 ⁻¹	>4.25x10 ⁴
	14	2.79	2.02x10 ⁻¹	2.11	2.51x10 ⁻¹	2.17x10 ⁵
	21	4.94	2.72x10 ⁻¹	2.86	3.35x10 ⁻¹	2.89x10 ⁵
	28	9.70	3.49x10 ⁻¹	4.18	4.23x10 ⁻¹	5.95x10 ³

Sediment Analysis-Chloramine Addition

PVC	7	2.5x10 ⁻²	1.3x10 ⁻²	0.95x10 ⁻²	0.76x10 ⁻²	1.27x10 ⁴
	14	1.78	2.3x10 ⁻¹	0.76x10 ⁻²	0.14x10 ⁻²	3.14x10 ³
	21	1.77	2.0x10 ⁻¹	0.85x10 ⁻²	0.57x10 ⁻²	1.18x10 ³
	28	9.6x10 ⁻¹	0.9x10 ⁻¹	2.10x10 ⁻²	0.38x10 ⁻²	2.1x10 ³
Cu	7	4.5x10 ⁻²	2.1x10 ⁻²	1.7x10 ⁻²	0.94x10 ⁻²	2.81x10 ²
	14	1.69	2.3x10 ⁻¹	1.7x10 ⁻²	1.7x10 ⁻²	8.75x10 ³
	21	8.6x10 ⁻¹	1.2x10 ⁻¹	1.7x10 ⁻²	1.2x10 ⁻²	9.5x10 ³
	28	9.1x10 ⁻¹	1.0x10 ⁻¹	1.9x10 ⁻²	0.56x10 ⁻²	4.22x10 ³
Steel	7	9.8x10 ⁻¹	1.3x10 ⁻¹	8.3x10 ⁻¹	1.1x10 ⁻¹	8.84x10 ³
	14	3.95	2.5x10 ⁻¹	1.96	2.33x10 ⁻¹	3.91x10 ³
	21	3.47	2.1x10 ⁻¹	1.99	2.4x10 ⁻¹	8.5x10 ³
	28	5.13	4.6x10 ⁻¹	3.32	3.6x10 ⁻¹	5.7x10 ³

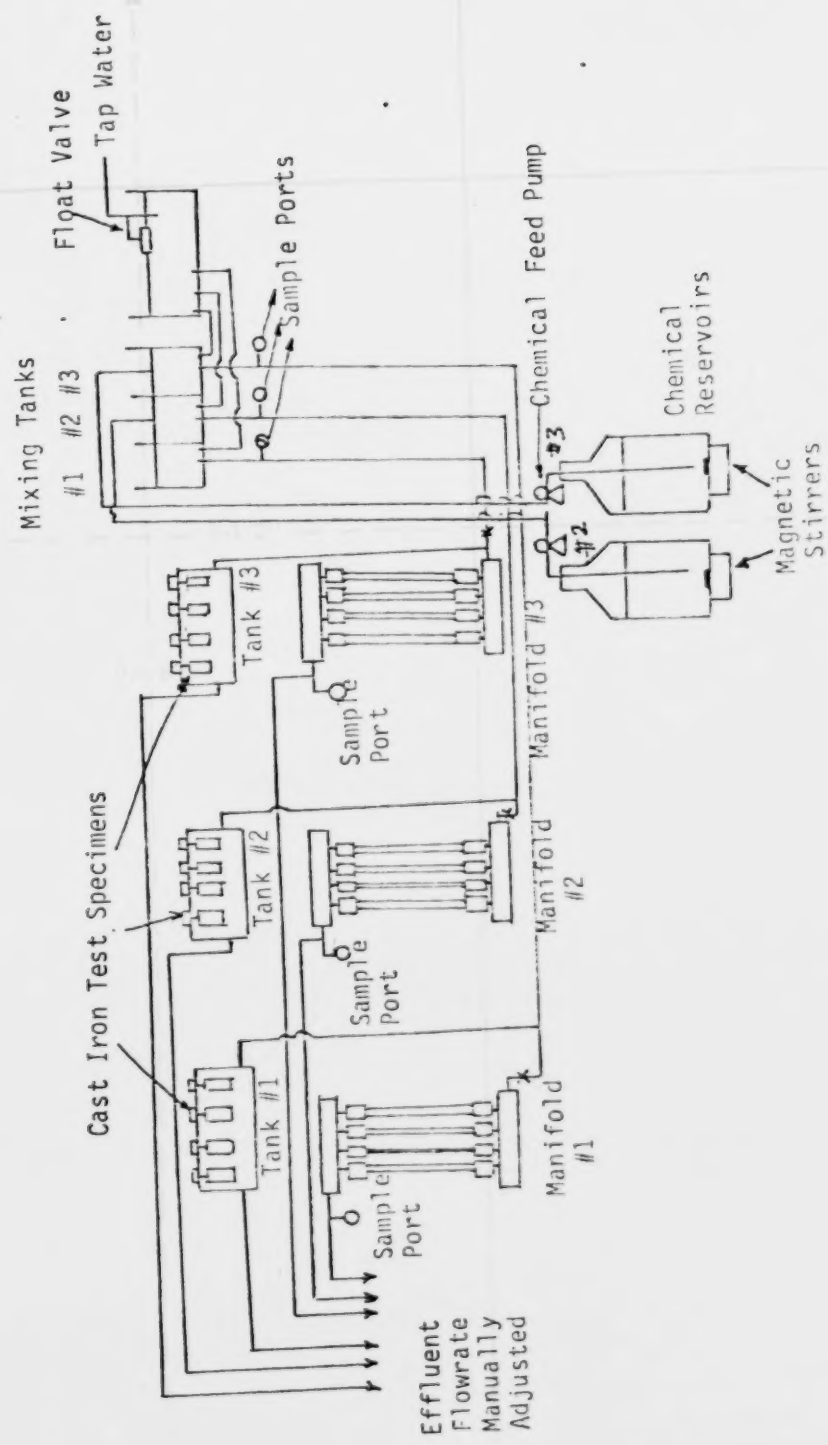


Fig. 28 Pipe Manifold System Schematic

As shown, each manifold and the tanks holding the cast iron test specimens were connected to an overhead mixing tank where the tap water could be mixed with a chemical solution pumped into the mixing tank from another reservoir. The flow through each manifold and tank was manually adjusted separately to a flow rate of about 200 ml/minute.

The experiment was initiated by allowing the laboratory tap water to flow into the mixing tanks, where it was mixed with the desired chemical. The treated water from the mixing tanks flowed through their respective manifold systems and the cast iron specimen tank. Water samples were taken from the mixing tanks and from the outlet of each manifold every 2 or 3 days. These samples were analyzed for pH, alkalinity, dissolved oxygen, total iron and standard plate count (SPC). Depending on the experiment, the levels of free chlorine, monochloramine and phosphates were also monitored. At the end of 7 days the four pipe sections from each of the three manifolds were removed. The inner surface of each pipe section was thoroughly scraped using a sterile rubber spatula and the sediments derived were washed with 200 ml of sterile, deionized water into a sterile plastic bottle. The sediment suspension was analyzed for total solids, total volatile solids, total non-filterable solids, total non-filterable volatile solids and SPC.

Table 47 describes the treatment of the tap water in each experiment.

During the course of the experiment the flow rate through the manifolds was close to the desired 200 ml/min, with some minor variations which sometimes affected the feed chemical concentrations.

The pH, D.O., alkalinity and SPC did not vary significantly during the experiments. However, during some experiments, the total iron concentration was observed to be significantly higher in the effluent. This was probably due to sloughing of attached iron-bearing sediments.

Tables 48 through 53 present the results of sediment analyses and cast iron corrosion rate in each manifold system with four removable pipe sections, identified as sections A, B, D, D.

The data presented in Tables 48 through 53 were analyzed statistically to determine if there were significant differences in the results. The dependent variables tested were total solids, non-filterable solids, and corrosion rate. Volatile solids and non-filterable volatile solids were not included in the analyses because of their low absolute values.

TABLE 47
TREATMENT SCHEDULE FOR MANIFOLD EXPERIMENT

Experiment Number	Treatment		
	Manifold Number 1	Manifold Number 2	Manifold Number 3
1	control (no treatment)	0.5 mg/l chlorine	2.0 mg/l chlorine
2	control (no treatment)	5 mg/l TG10* polyphosphate	10 mg/l TG10 polyphosphate
3	control (no treatment)	5 mg/l C-39* polyphosphate	10 mg/l C-39 polyphosphate
4	2.5 mg/l chloramine		2.5 mg/l chloramine + 5 mg/l TG10 polyphosphate
5	2.5 mg/l chloramine		2.5 mg/l chloramine + 5 mg/l TG10 polyphosphate
6	5 mg/l TG10 + 2.0 mg/l chlorine		5 mg/l C-39 + 2.0 mg/l chlorine

* Descriptions of these polyphosphates are included in Appendix C

Table 48 Sediment Analyses and Cast Iron Corrosion Rate - Experiment 1
(Temperature 22°C; pH = 7.8)

Treat- ment	Pipe Section	Total Solids* mg/cm ²	Total Vol- atile Solids* mg/cm ²	Nonfilter- able Solids* mg/cm ²	Nonfilterable Volatile Solids* mg/cm ²	Cast Iron Corrosion Rate, mdd
Control (Manifold #1)	A	1.73	0.39	0.68	0.06	62.57
	F	1.81	0.49	0.58	0.06	59.68
	C	1.41	0.39	0.47	0.05	64.57
	D	1.26	0.30	0.49	0.05	69.14
Chlorine 0.5 mg/l (Manifold #2)	A	2.34	0.50	1.68	0.18	58.29
	B	1.62	0.38	0.68	0.07	62.71
	C	1.70	0.36	0.88	0.09	54.43
	D	1.74	0.43	0.76	0.08	53.29
Chlorine 2.0 mg/l (Manifold #3)	A	2.28	0.40	1.02	0.11	50.71
	B	1.93	0.46	1.08	0.22	42.86
	C	2.31	0.46	1.38	0.14	50.29
	D	2.82	0.55	1.65	0.19	35.29

Table 49 Sediment Analyses and Cast Iron Corrosion Rate - Experiment 2
(Temperature 22°C; pH = 7.8)

Treat- ment	Pipe Section	Total Solids mg/cm ²	Total Vol- tile Solids mg/cm ²	Nonfilter- ble Solids mg/cm ²	Nonfilterable Volatile Solids mg/cm ²	Cast Iron Corrosion Rate mdd
Control (Manifold #1)	A	0.58	0.04	0.66	0.08	62.43
	B	1.06	0.16	0.56	0.07	59.86
	C	0.47	0.03	0.48	0.06	64.57
	D	0.90	0.10	1.15	0.14	69.14
TG-10 5 mg/l (Manifold #2)	A	1.64	0.18	1.90	0.22	58.14
	B	1.84	0.13	1.43	0.18	62.71
	C	2.06	0.36	1.53	0.19	54.43
	D	0.64	0.06	0.72	0.09	53.29
TG-10 10 mg/l (Manifold #3)	A	0.93	0.11	1.07	0.14	50.71
	B	1.25	0.14	1.38	0.18	42.86
	C	0.86	0.08	1.00	0.12	50.31
	D	1.32	0.15	1.73	0.21	35.29

Table 50 Sediment Analyses and Cast Iron Corrosion Rates - Experiment 3
(Temperature 22°C; pH = 7.8)

Treat- ment	Pipe Section	Total Solids mg/cm ²	Total Volatile Solids mg/cm ²	Nonfilter- able Solids mg/cm ²	Nonfilterable Volatile Solids mg/cm ²	Cast Iron Corrosion Rate mdd
Control (Manifold #1)	A	0.67	0.10	0.68	0.07	55.86
	B	0.73	0.10	0.71	0.07	63.99
	C	0.40	0.06	0.41	0.04	66.09
	D	0.72	0.08	0.75	0.07	70.71
C-39 5 mg/l (Manifold #2)	A	0.98	0.13	0.97	0.10	59.71
	B	0.94	0.12	1.06	0.09	70.85
	C	1.23	0.14	1.20	0.11	69.29
	D	0.23	0.04	0.22	0.02	74.71
C-39 10 mg/l (Manifold #3)	A	0.64	0.10	0.70	0.07	69.83
	B	0.78	0.11	0.79	0.08	71.43
	C	0.72	0.09	0.73	0.06	78.71
	D	0.79	0.10	0.81	0.08	79.86

Table 51 Sediment Analyses and Cast Iron Corrosion Rate - Experiment 4
(Temperature 22°C; pH = 7.8)

Treat- ment	Pipe Section	Total Solids mg/cm ²	Total Volatile Solids mg/cm ²	Nonfilter- able Solids mg/cm ²	Nonfilter- Volatile Solids mg/cm ²	Cast Iron Corrosion Rate mdd	SPC 2 #/cm ²
Chloramine 2.5 mg/l (Manifold #1)	A	0.72	0.08	0.66	0.07	70.86	1.3x10 ⁵
	B	0.84	0.11	0.80	0.10	69.29	3.9x10 ⁵
	C	0.61	0.07	0.50	0.06	67.86	9.9x10 ⁵
	D	0.53	0.08	0.46	0.05	65.71	2.3x10 ⁵
TG-10, 5 mg/l + Chloramine, 2.5 mg/l (Manifold #3)	A	1.15	0.15	1.11	0.11	72.00	2.8x10 ⁵
	B	1.36	0.14	1.28	0.12	74.57	1.9x10 ⁵
	C	1.22	0.11	1.13	0.10	78.29	--
	D	1.56	0.17	1.58	0.15	87.86	4.1x10 ⁵

Table 52 Sediment Analyses and Cast Iron Corrosion Rate - Experiment 5
(Temperature 22°C; pH ≈ 7.8)

Treat- ment	Pipe Section	Total Solids mg/cm ²	Total Volatile Solids mg/cm ²	Nonfilter- able Solids mg/cm ²	Nonfilter- Solids mg/cm ²	Cast Iron Corrosion Rate mdd	SPC #/cm ²
Chloramine 2.5 mg/l (Manifold #1)	A	0.58	0.08	0.46	0.15	51.62	2.0x10 ⁴
	B	0.66	0.09	0.47	0.07	55.62	1.2x10 ⁴
	C	0.67	0.10	0.55	0.09	70.21	1.4x10 ⁴
	D	0.56	0.09	0.44	0.07	71.93	7.7x10 ³
Chloramine 2.5 mg/l + TG-10 5.0 mg/l (Manifold #3)	A	1.08	0.14	0.96	0.12	64.21	6.2x10 ⁴
	B	1.35	0.16	1.29	0.16	59.63	3.6x10 ⁴
	C	1.10	0.14	1.19	0.14	69.93	6.0x10 ⁴
	D	1.35	0.17	1.58	0.18	54.60	3.6x10 ⁴

TABLE 53
SEDIMENT ANALYSES AND CAST IRON CORROSION RATE-EXPERIMENT 6
(Temperature 22°C; pH $\approx$ 7.8)

Treat- ment	Pipe Section	Total Solids mg/cm ²	Total Volatile Solids mg/cm ²	Nonfilter- able Solids mg/cm ²	Nonfilterable Volatile Solids mg/cm ²	Cast Iron Corrosion Rate mdd
Chlorine 2.0 mg/l +TG10 5 mg/l (Manifold #1)	A	1.17	0.12	0.87	0.07	55.48
	B	1.12	0.10	0.79	0.06	62.21
	C	1.01	0.10	0.84	0.07	67.07
	D	1.01	0.12	0.77	0.07	73.50
Chlorine 2.0 mg/l +(-39 5 mg/l) (Manifold #3)	A	1.64	0.15	1.34	0.11	79.22
	B	1.78	0.19	1.61	0.13	74.93
	C	1.29	0.13	1.12	0.08	74.50
	D	1.82	0.18	1.57	0.13	74.93

Initially, the mean, standard deviation and standard error of the mean were determined for each study. Since the variations of the mean within each experiment were sometimes quite large, an analysis of variance test was conducted. Further, Dunnett's test for multiple comparison with a control was used to determine which water treatment produced results which were significantly different from the control. For the variable, "total solids", it was concluded, using a 95% confidence limit, that treatments with 0.5 and 2.0 mg/l chlorine (Expt. 1), 5.0 mg/l TG-10 polyphosphate (Expt. 2) and 2.0 mg/l chlorine and 5.0 mg/l C-39 polyphosphate (Expt. 6) resulted in significantly greater total solid accumulations compared to the control.

For the variable, "non-filterable solids", it was concluded, using a 95% confidence limit, that treatments with 2.0 mg/l free chlorine (Expt. 1), 5.0 and 10.0 mg/l TG-10 polyphosphate (Expt. 2), 2.5 mg/l chloramine and 5.0 mg/l TG-10 polyphosphate (Expt. 4 and 5) and 2.0 mg/l chlorine and 5.0 mg/l C-39 polyphosphate (Expt. 6) resulted in significant increases in the non-filterable residue in the pipe sediment as compared to the control.

Cast iron specimens were observed to corrode more slowly after the water was treated with 2.0 mg/l chlorine (Expt. 1) and 10.0 mg/l TG-10 polyphosphate (Expt. 2), whereas the treatment provided by 10 mg/l C-39 polyphosphate (Expt. 3) and 2.0 mg/l chlorine and 5.0 mg/l C-39 polyphosphate (Expt. 6) were observed to increase corrosion rates.

To confirm the results of Dunnett's test, Duncan's multiple range test was conducted. Duncan's test compares each experiment with all the other experiments taken one at a time. It groups the experiments with no significant differences in the results. The results of Duncan's tests confirm the previous results within the 95% confidence limit.

The results of these manifold experiments can be summarized as follows:

- a. Microbial growth is related to TOC levels. TOC levels of 5.0 mg/l and lower limit the amount of microbial growth in pipe manifold systems.
- b. The addition of chlorine reduced microbial growth. Chlorine residuals of 1.0 mg/l and higher suppress microbial growth significantly. Chloramine doses in the range of 1 to 2 mg/l are not as effective.
- c. The presence of methane in source water stimulates

microbial growth. Methane concentrations of about 9 to 13 mg/l in the influent increased the amount of microbial growth in the system markedly. Many ground waters which have comparable amounts of dissolved methane present may therefore promote the growth of microorganisms in water distributions system.

- d. Studies of the effect of pipe materials on the sediment accumulation and biological growth on the pipe surface, showed that steel pipes developed the largest amount of attached sediment with time (35 days) compared to PVC or copper pipes. The major portion of the accumulation of steel pipe was non-filterable inert residue. Despite less accumulation on PVC and copper pipes, bacterial plate count data indicated that there was a comparable number of microorganisms in the sediments of all pipe materials, therefore, the potential for microbially mediated reactions may have been roughly equivalent in all three pipe materials.
- e. Bacterial plate counts on accumulations from pipe surfaces indicated that neither chlorine nor chloramine residuals prevented microorganisms from accumulating within the sediments attached to the pipe surface. This result may be of special importance to an understanding of how microbial processes can proceed in water mains even where low bacterial counts and sufficient disinfectant residuals are observed in samples of the bulk water.
- f. The addition of polyphosphate compounds TG-10 and C-39 (with and without the addition of the disinfectants chlorine and chloramine) sometimes resulted in increased deposition on pipe surfaces and sometimes in reduced deposition. The results were mixed and inconclusive.

SECTION 6

WATER QUALITY STUDIES USING SIMULATED PIPE LOOP SYSTEMS

INTRODUCTION

Early studies of a number of water distribution systems indicated that water quality changes in distribution systems were related to the growth of microorganisms in those systems. The significance of the microbial growth had to be evaluated in terms of their potential interaction with the various chemicals in water as well as the sediments that had already formed in the distribution mains.

A laboratory-scale pipe loop system was constructed to simulate a part of a water distribution system. Experiments were conducted with laboratory tap water, and water quality changes were monitored with time. Only the pertinent water quality parameters were measured and related to the microbial growths.

Since red water is the most frequently encountered water quality problem in distribution systems, experiments were directed toward evaluating the role of microorganisms in influencing the corrosion process of iron pipe materials.

Materials and Methods

A. Experimental Apparatus

A simulated pipe system was constructed as shown in Figure 29. The pipe system consisted of six enclosed stainless steel basins, i.e., two influent basins (30x25x61 cm) and four holding basins (30x25x20 cm). Four 18.3 m long test pipe loops were constructed with 2.5 cm diameter PVC and low carbon steel pipes. The test water source was the University of Missouri-Columbia laboratory tap water.

One influent water line was connected to a membrane filtering system (0.45 μ m pore size membrane cartridge unit) for the removal of microorganisms. A pipe section with a control valve was installed before the filtering system in

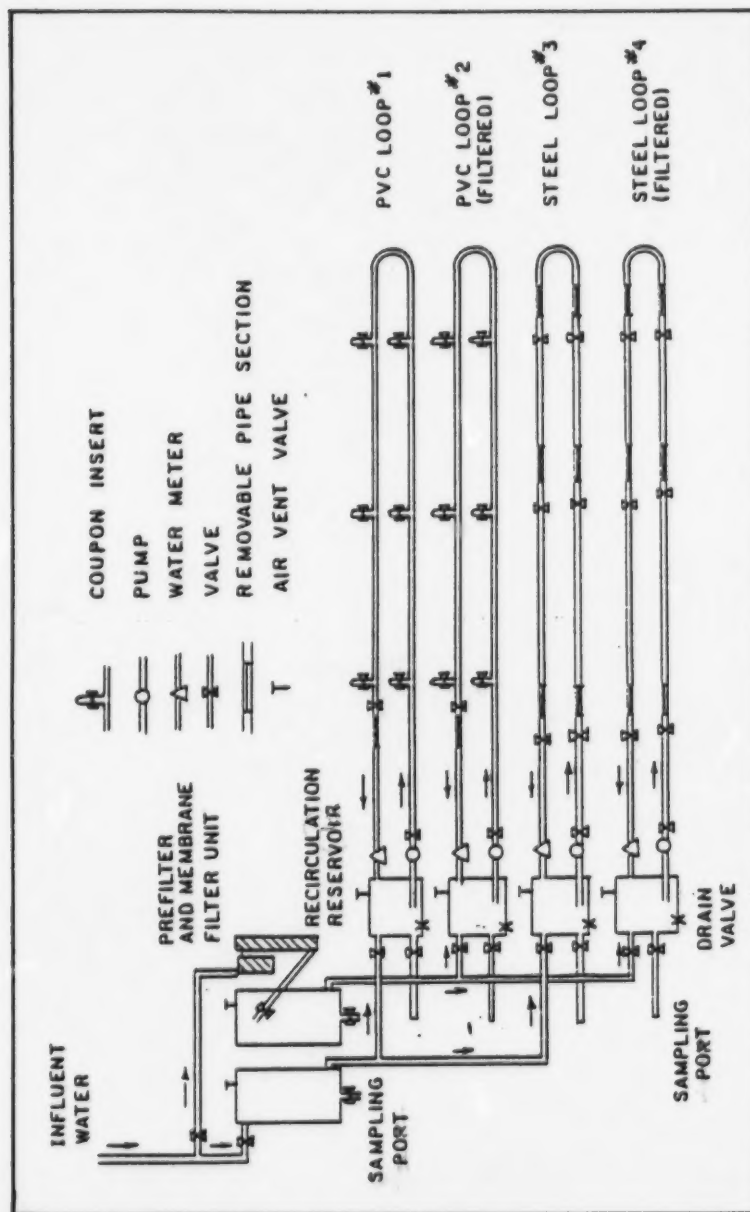


Fig. 29 Schematic Diagram of PVC and Steel Pipe Loop Systems

order to allow the application of disinfectant to the test water. The filter system consisted of a membrane filter cartridge and was installed to remove any sediments and micro-organisms in the influent water. The filtered water then entered an influent basin. The second water line was connected directly to an influent basin without any filtration and disinfection. When each influent basin was filled with either filtered or unfiltered test water, inlet valves of four holding basins were opened in order to feed the water into either a PVC or a steel loop system. A water-lubricated circulating pump (Grundfos UPS 20-42F) and a water meter were installed in each loop system to recycle the water and to measure the amount of water being circulated during the test period.

B. Experimental Methods

Experiments were conducted with the simulated pipe system using UMC laboratory tap water without any supplementary nutrients. The test water was recirculated at a velocity of 1.52 m per second. Other recirculation rates studies were 3.66 m per second and 0.91 m per second.

Selected loop systems, i.e., one PVC and one steel loop system, were disinfected by recirculating a chlorine solution. The chlorine dosage ranged from 50 mg/l to 155 mg/l. The contact time ranged from four hours to 19 hours. Thereafter, the chlorinated water was diluted with filtered tap water until only a trace amount of chlorine residual remained in the system.

Before each experiment both prefilter and membrane filter cartridges were placed in their respective stainless steel casings and sterilized in an autoclave. The connecting plastic tubes were disinfected by soaking in a 100 mg/l chlorine solution.

After recirculating the water for a period of time, aliquots for chemical and micro-biological analyses were taken at the influent and holding basin outlets. Prior to sampling, all sampling outlets were disinfected with 70% alcohol. After each sampling, the sample water removed was subsequently replenished with the UMC laboratory tap water.

The following chemical and microbiological parameters were analyzed on the water samples collected from the loop system: pH, alkalinity, hardness, dissolved oxygen, total iron, sulfate, hydrogen sulfide, total organic carbon, ammonia, phosphate and bacterial plate counts. The same methods of analyses were employed as described in Chapter 5. However,

the following changes were incorporated in analytical methods to facilitate the overall analyses. The Ferrozine method of iron analysis was employed because it was very simple to conduct (99). For determination of low concentrations of iron in water, the Ferrozine method is more accurate than the 1, 10-Phenanthroline method. Previously hydrogen sulfide was analyzed by the iodometric titration method. This method was replaced by the methylene blue method for sulfide analysis (100). Both Winkler method and the dissolved oxygen meter were used to measure the dissolved oxygen concentrations in water. For total organic carbon, the ultra-low level total organic carbon analyzer* was utilized to measure the low level TOC in test water.

Microbiological analyses included the routine bacterial plate counts on the Standard Method agar at 25°C incubation for seven days. Other microbiological analysis included determination of other groups of microorganisms in pipe loop systems.

The microorganisms which were cultured on various selective enrichment culture media were iron, sulfur and nitrogen-transforming organisms, iron-precipitating, sulfate-reducing, sulfur-oxidizing/precipitating, nitrifying, nitrogen-fixing and denitrifying organisms. Aerobic and facultative anaerobic heterotrophic organisms were randomly selected and further subcultured to obtain the pure culture forms. The Analytab product, API/20E, a preset battery of 20 microtubes for the performance of 22 biochemical tests for identification of Enterobacteriaceae and other Gram negative bacteria, and Corning's non-fermenter system, another commercial identification system for Gram negative bacteria, were utilized to identify the isolates from loop system water.

Results and Discussion

A. Pipe Loop Study: Short-Term Experiments for the Evaluation of Test Apparatus:

To determine the limitations and capabilities of the experimental apparatus, three short-term experiments were performed. The rate of recirculating water flow was 0.91 meters per second.

The results of the first short-term experiments are presented in Table 54. The iron concentration of the filtered influent water was negligible, while that of the unfiltered influent was 0.035 mg/l. After 24 hours, the total iron concentrations were found to have increased in both the

*Dohrmann TOC Analyzer, Model No. TC 54

Table 54 Dissolved Oxygen and Total Iron in Pipe Loop System Water
(Period: January 18 - 26, 1978)

Time of Operation	PVC Loop No. 1		PVC Loop No. 2		Steel Loop No. 3		Steel Loop No. 4	
	Dissolved Oxygen, mg/l	Total Iron, mg/l	Dissolved Oxygen, mg/l	Total Iron, mg/l	Dissolved Oxygen, mg/l	Total Iron, mg/l	Dissolved Oxygen, mg/l	Total Iron, mg/l
EXPERIMENT #1								
Initial	8.8	0.03	8.8	0.04	8.8	0.03	8.8	0.04
1 day	6.4	0.30	5.7	0.53	5.1	0.34	1.1	0.99
2 days	5.9	0.19	3.6	0.39	0.8	1.08	0.6	1.70
EXPERIMENT #2								
2 days	8.7	0.03	8.7	0.03	8.7	0.09	8.7	0.05
6 days	6.3	0.14	3.0	0.21	1.6	1.15	1.2	0.51
EXPERIMENT #3								
6 days	8.7	0.11	8.7	0.32	9.2	0.62	8.7	0.34
7 days	7.3	0.10	6.7	0.10	1.6	0.55	1.0	0.42
8 days	8.0	0.10	7.0	0.08	1.1	0.42	1.0	0.37

PVC and steel pipe systems. Further increases in total iron concentration were observed principally in the steel pipe loop systems. A portion of each recirculating pump was made of low carbon steel. Increases in iron concentrations in PVC pipe systems were attributed to the oxidation of the steel parts in the recirculating pumps. The availability of both chlorine and dissolved oxygen in water had resulted in the oxidation of iron constituents in all loop systems.

Depletion of dissolved oxygen was clearly evident in all loop systems. Within 48 hours, up to 93 percent of the dissolved oxygen was utilized in the steel pipe system (Loop No. 4). In the PVC pipe system, the decrease in dissolved oxygen was 33 to 95 percent. The oxygen depletion in the steel systems is related to high total iron concentrations.

Two more short-term experiments were conducted subsequently. In the last of these short-term experiments, the concentration of iron found in the pipe loop systems was higher than that of the previous two experiments. In spite of vigorous efforts to flush the corrosion products formed during the earlier experiments, significantly higher amounts of iron were observed. After evaluating the results of these short-term experiments, it was decided that some modifications to the experimental apparatus were needed. These included: (1) a drain spout and a sight glass for all basins; (2) a 30 cm long PVC pipe section for the addition of disinfectant; and (3) a 0.22 μ membrane filter cartridge in place of a 0.45 μ membrane filter cartridge.

When bacteria were observed in water samples taken from loop systems which had been chlorinated and filtered through a 0.45 μ membrane filter cartridge, experiments were repeated in an effort to obtain bacteria-free pipe loop systems. Higher chlorine dosages (up to 176 mg/l) and longer contact time (up to 96 hours) were applied to the influent basin which subsequently supplied one PVC and one steel pipe loop system. The results were rather surprising in that a bacteria-free system could not be established and maintained. Only the continued presence of a chlorine residual maintained a bacteria-free system.

The results of an experiment conducted to evaluate the regrowth of the organisms in the system are shown in Table 55. A "bacteria-free" loop system was attained in both PVC and steel pipes when significant chlorine residuals were present in loop water. The concentration of disinfectant required to maintain a bacteria-free system differed significantly between the PVC and the steel pipe loop systems. Bacterial

Table 55 Bacterial Counts and Chlorine Residuals in Filtered Tap Water in Pipe Loop Tests

Day	Elapsed Time, hrs.	Chlorine Residuals, mg/l	Influent Tank Bacterial Count at 35°C, no./ml	Bacterial Count at Rm. Temp.* no./ml	Chlorine Residuals, mg/l	PVC Loop System No. 2 Bacterial Count at 35°C, no./ml	Bacterial Count at Rm. Temp.* no./ml	Steel Loop System No. 4 Chlorine Residuals, mg/l	Bacterial Count at 35°C, no./ml	Bacterial Count at Rm. Temp.* no./ml
Initial	0	0	NM	NM	0	3.9×10^4	5.3×10^4	0	2.5×10^4	3.2×10^4
1	24	30	0	0	30	0	0	30	0	0
	28	30	0	0	30	0	0	20	0	0
	31	15	0	0	25	0	0	20	0	0
	46	12	0	0	15	0	0	7	144	184
2	53	10	1	1	15	0	0	trace	14	16
	55	trace	8	12	6	0	0	0	0	1
3	70	trace	726	551	5	0	0	trace	TNTC	1197
	78	trace	TNTC	TNTC	1	0	0	0	TNTC	TNTC

Initial applied Chlorine dose: 35 mg/l
Room temperature: 25 - 28°C

Experimental Period: September 8-11, 1978

regrowth, as evidenced by the increase in bacterial counts in water, was observed in the steel pipe systems. Bacteria were observed in the steel system even when the water contained 7 mg/l chlorine residuals. Unfortunately, bacteria were observed in all loop systems in spite of other carefully controlled and monitored experimental conditions, such as the sterilized filtering system, smaller pore size membrane filter (0.22 μ), aseptic sampling techniques, etc.

B. Pipe Loop Study No. 1: High Recirculation Rate

The first experiment of pipe loop study was conducted using UMC laboratory tap water at a water recirculation velocity of 3.66 m per second. Water samples were aseptically collected at the four holding basin outlets to determine the water quality changes in the loop systems. During this study the water temperature ranged between 20°C - 25°C.

The results of the dissolved oxygen concentrations in loop system water are shown in Figure 30. Although the PVC pipe loop (No. 1) and the steel pipe loop (No. 3) were chlorinated and filtered before the experiment, the resultant water quality changes were similar to those of the parallel systems, the PVC pipe loop No. 2 and the steel pipe loop No. 4. After the initial sharp decrease, the dissolved oxygen concentrations in all loop systems remained relatively constant. After 51 hours, the average decrease in the dissolved oxygen concentration in the steel pipe loop systems was about 86 percent while that of the PVC pipe systems was about 20 percent of the initial concentration.

Data on total iron concentrations are summarized in Table 56. All loop systems exhibited an initial increase in iron concentrations. The observed change is attributed to the corrosion of cast iron specimens and steel pipe material in loop systems. Generally, the iron concentrations of the PVC pipe systems were lower than that of the steel pipe systems with one exception. The PVC loop system No. 1 had an anomalous iron value after about 380 hours of experimental time. A possible sloughing of attached iron oxide precipitate is suggested for this increase in iron concentrations.

The iron concentrations in the two steel loop systems fluctuated extensively. The iron concentration in steel loop system No. 3 decreased to about 0.1 mg/l at 24 hours, then gradually increased to a peak value of 1.88 mg/l after 900 hours whereas iron concentrations in steel loop No. 4 fluctuated within the range of 0-0.4 mg/l throughout the experimental period. The recirculation velocity of 3.66 m per second lies within the region of turbulent flow. Therefore, it is assumed that the shear forces on pipe walls may have caused

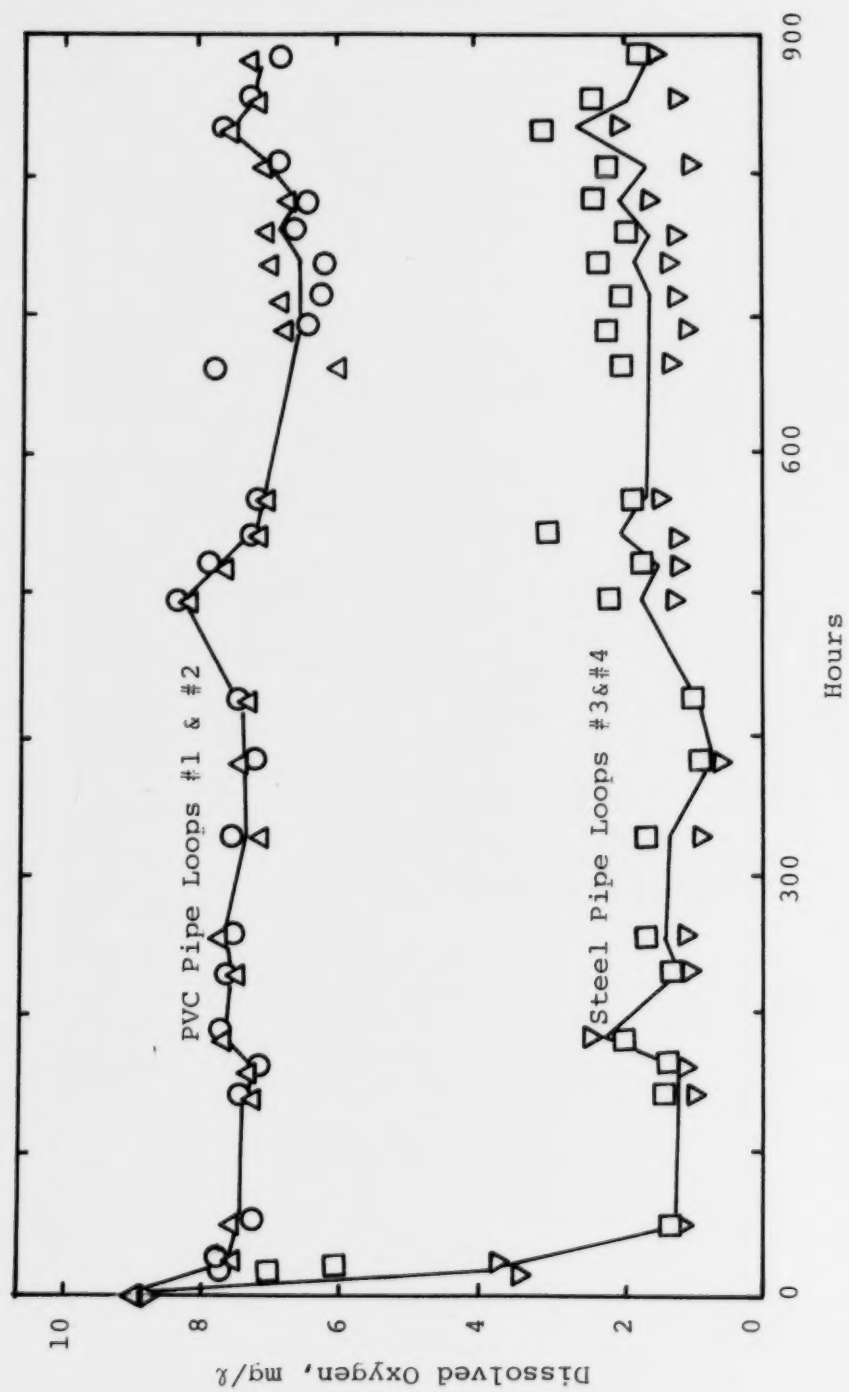


Fig. 30 Dissolved Oxygen in Pipe Loop System Water (March 7 - April 14, 1978)

Table 56 Total Iron Concentration in Pipe Loop System Water

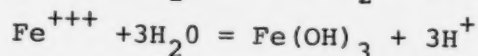
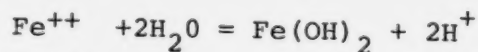
Elapsed Time, hrs.	Total Iron Concentration, mg/l			
	PVC Loop No. 1	PVC Loop No. 2	Steel Loop No. 3	Steel Loop No. 4
Start	0.09	0.05	0.29	0.16
17	0.35	0.35	0.86	0.44
24	0.01	0.04	0.12	0.10
51	<0.01	<0.01	0.18	0.39
145	0.02	0.02	0.10	0.08
163	0.01	<0.01	<0.01	<0.01
186	0.06	0.07	0.18	0.20
232	0.02	0.02	0.08	0.11
257	0.02	0.06	0.07	0.10
330	0.16	0.09	0.10	0.31
384	0.64	0.04	0.14	0.08
402	0.40	0.03	0.10	0.10
427	0.33	0.01	0.15	0.06
498	0.12	0.01	0.37	0.12
522	0.05	0.03	0.16	0.10
546	0.09	0.03	0.26	0.15
570	0.08	0.05	0.19	0.27
666	0.06	0.05	0.25	0.36
691	0.04	0.04	0.30	0.19
714	0.06	0.06	0.27	0.16
739	0.06	0.06	0.39	0.15
762	0.05	0.05	0.42	0.11
785	0.04	0.04	1.80	0.08
810	0.04	0.03	0.76	0.07
835	0.06	0.04	0.76	0.10
857	0.04	0.04	1.34	0.08
888	0.88	0.50	1.88	0.24
1224	0.05	0.09	NM	NM

intermittent dislodging of accumulated deposits and yielded the resultant variation in the iron concentrations of loop water.

Some trace of hydrogen sulfide was detected after three weeks of recirculation in both the PVC and the steel pipe loop systems.

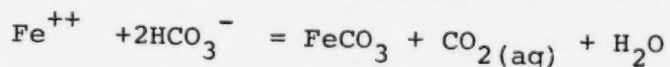
The results of the analysis for pH and alkalinity are presented in Figure 31. In general, the pH and alkalinity for water in PVC loop systems remained relatively constant. Some minor variations of pH were noted initially and after 700 hours of the experiment. The alkalinity of the water in both steel loop systems continually decreased during the experimental period.

The decrease in alkalinity of the water in the steel loop systems could result from the hydrolysis of oxidized iron (Fe^{++} or Fe^{+++}) which was derived from the corrosion of steel pipe.

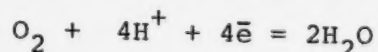


Since the loop water contained about 4-5 meq/l of total alkalinity, hydrogen ion produced from the hydrolysis or iron will react to decrease alkalinity as well as lower the pH.

Another possible reaction may be the formation of ferrous carbonate and calcium carbonate at pipe wall surfaces.



The precipitation of ferrous carbonate is possible within the neutral pH range. However, the precipitation of calcium carbonate requires higher pH. It is assumed that when iron is oxidized and oxygen accepts electrons to form water,



hydrogen ions are consumed. The net increase in OH^- ions near corroded iron metal then provides conditions conducive to calcium carbonate precipitation on the metal surface.

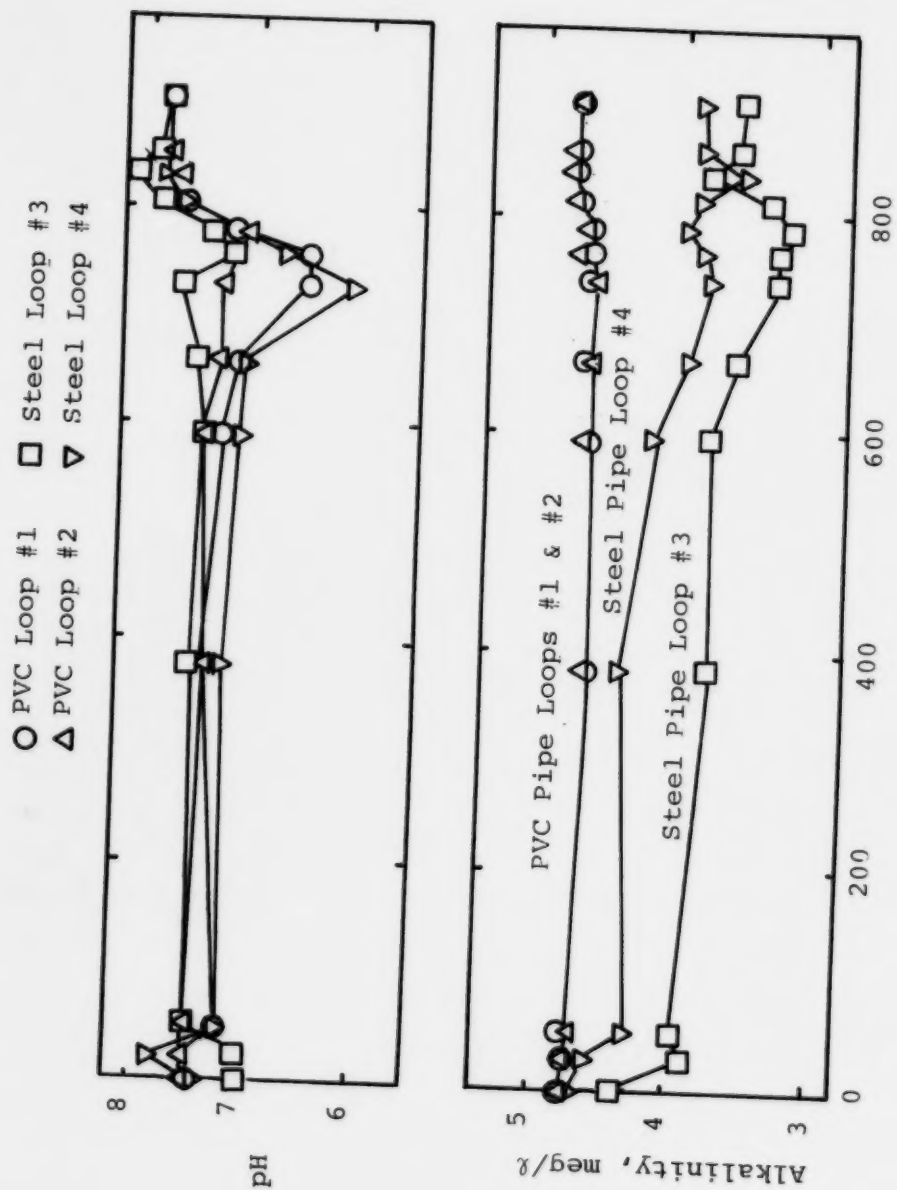


Fig. 31 pH and Alkalinity of Pipe Loop System Water
(March 7 - April 14, 1978)

To decrease the pH of water from 7.1 to 6.1, there would have to be at least 0.02 meq of hydrogen ion produced per loop volume (28 liters) of water. This would be equivalent to 0.88 mg of dissolved carbon dioxide.

Iron oxidation in steel loop systems is indicated by the appearance of rusty-colored hydrated ferric oxide precipitates on pipe surfaces.

The carbon dioxide may be produced by microbial activities in loop systems. Experimental data are not available in determining the actual carbon dioxide yield.

The standard plate count was measured as an indicator of the microbial growth. The methodology of plate count was modified in an effort to better evaluate microbial population. The enumeration of viable counts was performed after the standard method agar plates had been incubated at room temperature for about seven days (Table 57).

After 384 hours of recirculation, the PVC loop system No.1 exhibited a three or four order of magnitude increase in bacterial counts while the increase in other loop systems was only one to two orders of magnitude. The observed decrease in pH of water from loop system No. 1 may be attributed to the higher production of carbon dioxide, since the highest net increase in organism growth was observed in this system.

In general, the UMC laboratory tap water appeared to be capable of supporting up to 10^5 organisms per ml. Even after 900 hours, 5,000 to 30,000 organisms per ml of water were observed in the pipe loop systems. A variety of pigmented and non-pigmented bacteria was observed in the standard plate count medium. Other microorganisms observed were iron-precipitating organisms, yeasts, nitrogen-fixing and denitrifying bacteria. Samples taken after three weeks to examine for the presence of sulfate-reducing organisms yielded negative results. However, the sulfur-oxidizing organisms were observed in loop systems Nos. 1, 3 and 4.

C. Pipe Loop Study: Reduced Recirculation Rate

Another experiment was conducted with the simulated pipe loop system using the UMC laboratory tap water. The rate of water recirculation was adjusted to 1.52 m per second. The flow rate was lowered to more closely simulate actual flow conditions in distribution systems.

Before initiating this experiment, the influent inlet pipes were switched because the filter system was relocated

Table 57 Bacterial Plate Counts in Water Pipe Loop System

Elapsed Time (hours)	Bacterial Plate Counts, number/ml			
	PVC Loop No. 1*	PVC Loop No. 2	Steel Loop No. 3*	Steel Loop No. 4
0	1.8×10^1	2.8×10^2	1.1×10^1	3.6×10^2
384	1.3×10^5	6.5×10^4	2.5×10^3	8.0×10^3
594	1.1×10^5	1.4×10^4	1.5×10^4	1.5×10^4
666	9.6×10^4	6.2×10^4	1.3×10^4	7.9×10^3
714	1.2×10^5	3.2×10^5	1.8×10^4	3.9×10^3
904	3.0×10^4	2.4×10^4	3.0×10^4	5.0×10^3

* In Loop 1 and 3, the water was initially pretreated with chlorine and membrane filtered with 0.45 μ m filter cartridge. In Loops 2 and 4, the water did not receive any pretreatment.

for easier manipulation. Therefore, in contrast to the previous experiment the other pair of pipe loop systems, i.e., loop No. 2 and loop No. 4 had received the pretreatment, while the parallel systems, Nos. 1 and 3 did not.

The standard plate counts (Standard Method) of the test water following disinfection and membrane filtration were zero organisms in 10 ml sample. However, the bacterial concentration of tap water was 714 organisms per ml when enumerated on the standard method agar after seven days incubation at 22°C to 28°C. When bacterial plate counts were performed on the pretreated water according to this modified method, there were 12 viable colonies per ml of water.

Since each sampling utilizes approximately three percent of the loop water volume, the average residence time of the test water was 20 to 40 days.

The results of chemical and microbiological analyses for the influent water to each pipe loop system are presented in Table 58 through 60. Table 59 and 60 indicate the chemical and microbiological water quality in influent basins with pretreatment. Table 58 presents water quality data without pretreatment. Figures 32 through 34 represent the pipe loop water quality data. Figure 32 shows the changes in dissolved oxygen concentrations for both the PVC and steel pipe loop system. The sudden increase in D.O. in loop Nos. 2 and 4 at 309 hours was due to restarting these loops with rechlorination and flushing since the bacterial counts in the feed water had become quite high (Table 59).

In general, the results of dissolved oxygen measurements confirmed the previous observations, i.e., an initial sharp decrease in dissolved oxygen concentrations in all systems. As expected, a greater depletion in dissolved oxygen concentration was observed in both the steel pipe loop systems than in the PVC pipe loop systems.

In this study each PVC loop system contained 12 cast iron test specimens. Perhaps, for this reason a higher reduction of dissolved oxygen was observed in the PVC loop systems. Test water temperatures were also markedly different between the two experiments. During this experiment there were periods when the test water temperatures were exceptionally high, 32°C - 35°C. The solubility of dissolved oxygen decreases with the increasing temperature of water. Therefore, the dissolved oxygen concentrations of both the influent and the test loop water were low, especially during the period of 900 - 1200 hours. The influent dissolved oxygen concentrations ranged from 6.4 - 6.7 mg/l during this experimental

Table 58 Chemical and Microbiological Analyses of Unfiltered UMC Tap Water
(Experimental Period: June 2 - July 15, 1978)

Elapsed Time hrs.	Dissolved Oxygen mg/l as O ₂	Total Iron as Fe	Hydrogen Sulfide mg/l as S	pH	Alkalinity meq/l	Total Hardness mg/l	Sulfate mg/l as SO ₄	Phosphate mg/l as P	Bacterial Plate Count* no./ml
0	7.7	0.04							7.1 x 10 ²
1	7.6	0.05							5.8 x 10 ²
26	8.3	0.06							4.7 x 10 ⁴
49	8.0	0.02		6.9	5.04	235	34		1.1 x 10 ³
97	7.8	0.02						0.004	1.5 x 10 ³
121	8.0	0.02							6.3 x 10 ⁴
168	7.7	0.06							7.0 x 10 ³
191	7.5	0.04	0.02	6.9			31		1.5 x 10 ²
262		0.04				236	31		3.6 x 10 ²
309	7.4	0.03			4.88	236	34		1.5 x 10 ²
20		0.02				234	32		1.8 x 10 ³
45	7.8	0.02				244			4.0 x 10 ³
92	7.3	0.02				236	32		1.1 x 10 ⁴
144	7.3	0.03							1.8 x 10 ³
161	7.4	0.02						0.009	9.6 x 10 ³
184	7.3	0.06				240	31		2.7 x 10 ⁴
209	7.6	0.02	0.02		4.96	239	32		
305	7.0	0.08	0.02		4.72	237	30		
401	6.7	0.05	0.02	7.9	4.78	236	29		3.5 x 10 ⁴
450	6.6	0.01		7.9	4.94	238	36		2.0 x 10 ⁴
498	7.0	0.08		7.9	4.86	238			
617									
689			0.02			237	30		
739	7.6	0.04		7.8	4.90	242	29		2.8 x 10 ⁴

* Cultivation Condition: Incubated at 220-280C for 5 days

Table 59 Chemical and Microbiological Analyses of Filtered UMC Tap Water
(Experimental Period: June 2 - June 14, 1978)

Elapsed Time hrs.	Dissolved Oxygen mg/l as O ₂	Total Iron as Fe	Hydrogen Sulfide mg/l as S	pH	Alkalinity meq/l	Total Hardness mg/l	Sulfate mg/l as SO ₄	Phosphate mg/l as P	Bacterial Plate Count* no./ml
1	7.6	0.02		7.0	5.04	238			1.2 x 10 ¹
26	8.3	0.04							1.1 x 10 ²
49	8.0	0.02			5.04	235	34		3.6 x 10 ²
97	7.9	0.02						0.004	3.0 x 10 ³
121	7.9	0.02					32		1.6 x 10 ⁴
168	7.9	0.03							1.6 x 10 ⁵
191	7.8	0.01	0.02	7.0			31		2.1 x 10 ⁵
262					4.68	234	30		2.8 x 10 ⁵
309	7.4	0.02				236			2.8 x 10 ⁵

* Cultivation condition: Incubated at 22^o - 28^oC for 5 days.

Table 60 Chemical and Microbiological Analyses of Filtered UMC Tap Water
(Experimental Period: June 14 - July 15, 1978)

Elapsed Time hrs.	Dissolved Oxygen mg/l as O ₂	Total Iron as Fe	Hydrogen Sulfide mg/l as S	pH	Alkalinity meq/l	Total Hardness mg/l	Sulfate mg/l as SO ₄	Phosphate mg/l as P	Bacterial Plate Count* no./ml
20	8.0	0.01				234	34		1.0 x 10 ¹
45	7.8	0.02				236			1.0 x 10 ²
92	7.2	0.02				236	30		9.2 x 10 ⁴
144	7.2	0.01							9.2 x 10 ³
161	7.2	0.00							2.2 x 10 ⁴
184	7.3	0.02				240		0.009	2.7 x 10 ⁴
209	7.6	0.01	0.02		4.84	233	33		2.7 x 10 ⁴
305	7.1	0.02	0.02	7.3	4.72	235	30		2.9 x 10 ⁴
401	6.7	0.02	0.02	7.9	4.70	234	27		
450	6.4	0.02		8.0	4.96	238	34		6.1 x 10 ⁴
498	6.6	0.01		7.8	4.84	232	33		1.1 x 10 ⁵
617									
689			0.0			239	30		
739	7.4	0.00		7.9	4.96	241	30		1.1 x 10 ⁴

* Cultivation condition: Incubated at 22^o - 28^oC for 5 days.

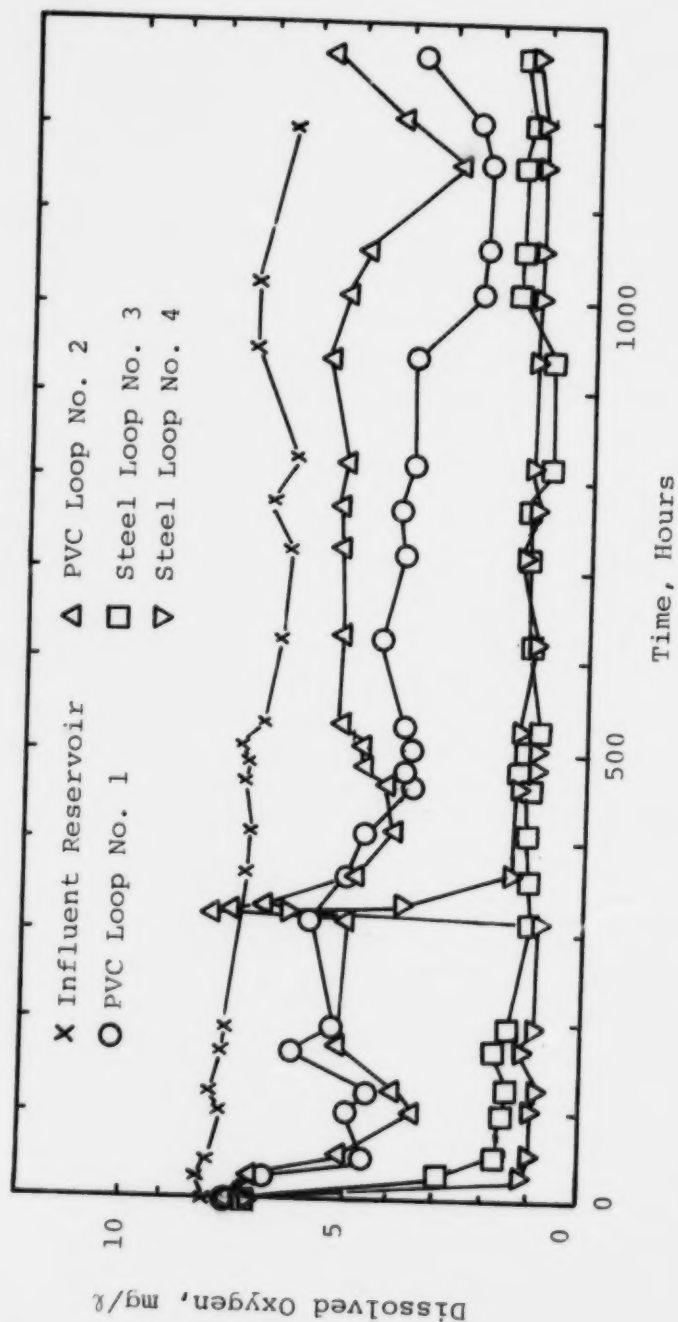


Fig. 32 Dissolved Oxygen in Pipe Loop System Water (June 2 - July 15, 1978)

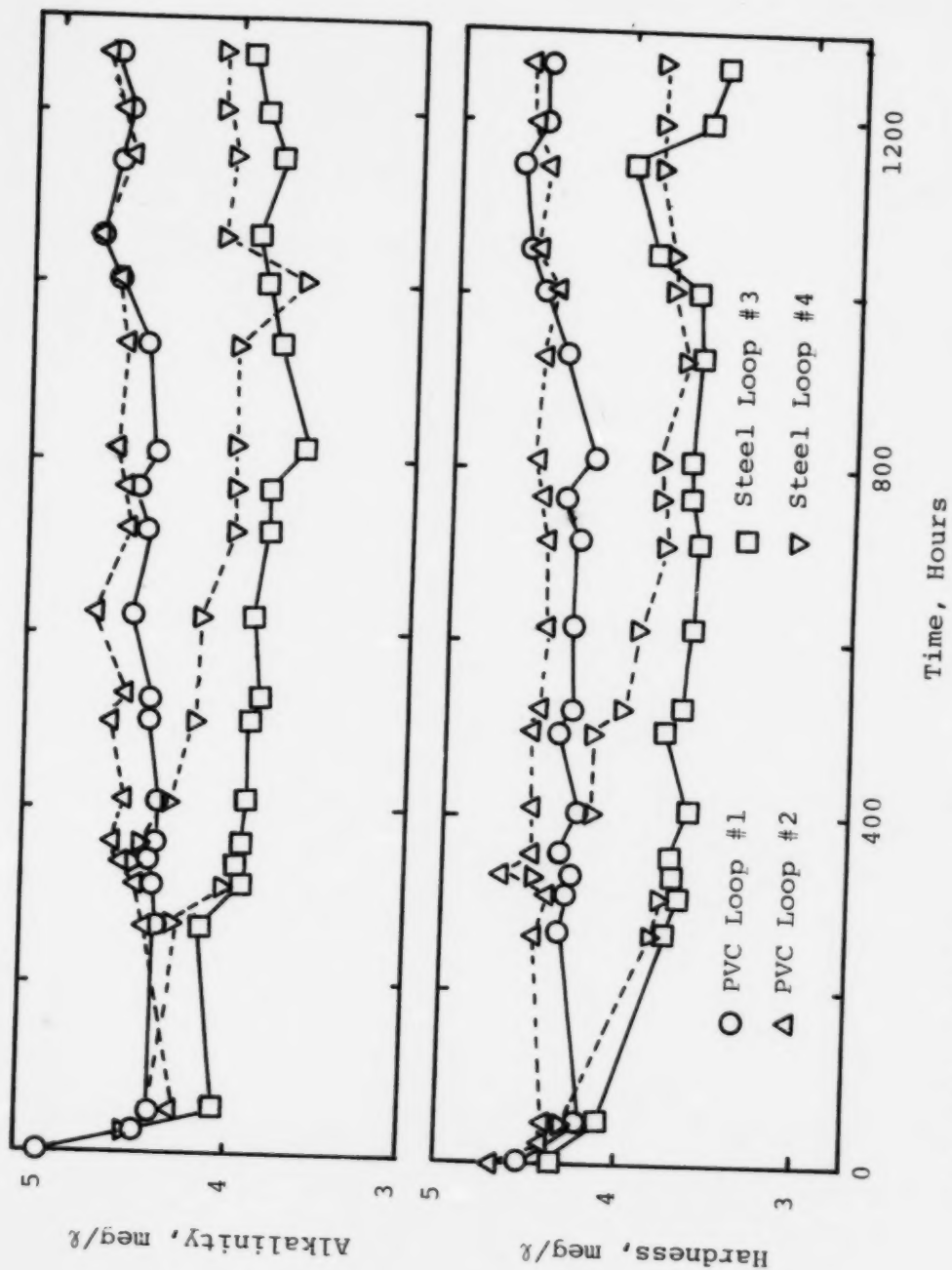


Fig. 33 Alkalinity and Hardness of Pipe Loop System Water
(June 2 - July 15, 1978)

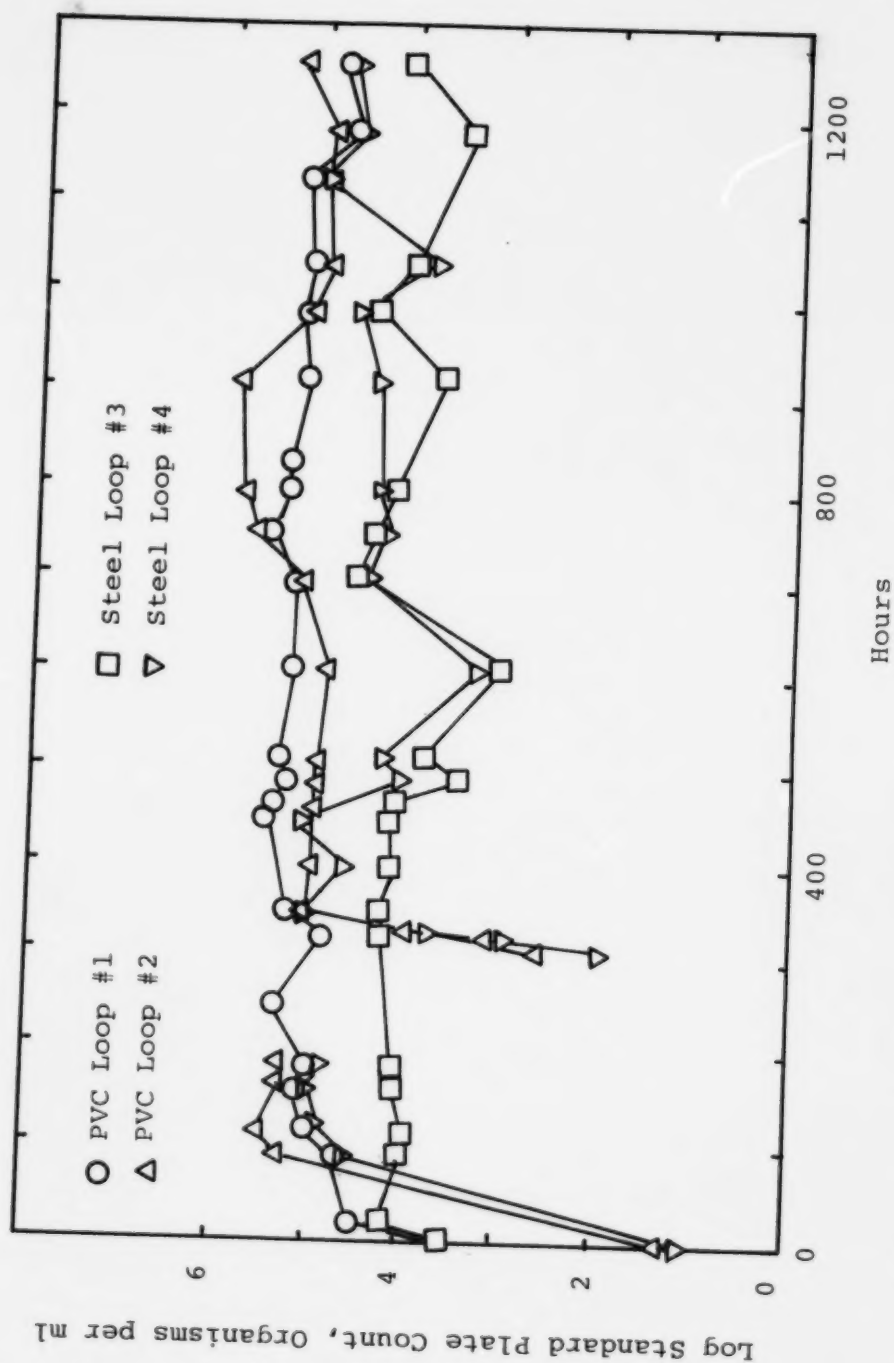


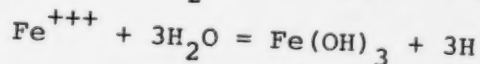
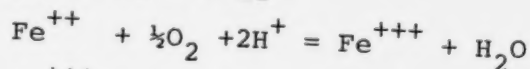
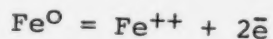
Fig. 34 Bacterial Plate Counts in Pipe Loop System Water
(June 2 - July 15, 1978)

period. An increased rate of iron oxidation at higher temperature might have increased the amount of oxygen uptake in PVC loop water.

The major uptake of dissolved oxygen in the steel loop systems was observed within the first 48 hours of the experiments. After 48 hours, the dissolved oxygen concentrations remained relatively constant for both steel loop systems.

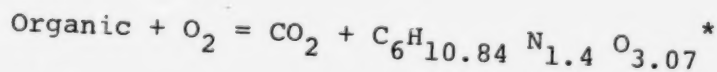
There are at least three major pathways which the dissolved oxygen in the loop water could be involved:

(1) Oxygenation of iron



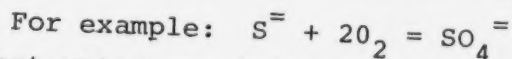
(2) Oxygen as the final electron acceptor in cellular respiration

microorganisms*



(bacterial cell)

(3) Reactions with reduced substances in water



When the test water was initially introduced into the pipe loop systems, within minutes the oxygenation of iron was observed as evidenced by the appearance of hydrated ferric oxides (rust) on pipe surfaces and disappearance of dissolved iron in loop water.

Stumm and Lee (101) found the rate of oxygenation of iron (II) to iron (III) solutions of pH greater than 5.5 to be first order with respect to the concentrations of both iron (II) and oxygen and second order with respect to the hydroxyl ions. The results of the initial pipe loop water quality were pH 7, dissolved oxygen 7.6 mg/l and temperature 20°C. Under this condition the oxygenation of iron (II) to iron (III) could readily occur. In fact the rate of solubilization of iron (II) would be extremely slow (101) since

$$\frac{-d[\ln \text{Fe(II)}]}{dt} = \frac{k_H [\text{O}_2(\text{aq})]}{[\text{H}^+]^2}, \text{ where}$$

$$k_H = 3 \times 10^{-12} \text{ min}^{-1} \text{ mole}^{-1} \text{ liter}^{-1} \text{ @ } 20^\circ\text{C}.$$

This would imply that the rate limiting reaction in overall oxidation of iron to be the oxidation (corrosion) of iron metal to iron ions, Fe(II).

The analysis of dissolved oxygen concentrations in steel loop system water yielded a nearly 87 percent decrease after 48 hours. The dissolved oxygen concentrations in steel loop systems remained relatively constant after 48 hours. In other words, the major oxidation-reduction reaction between the iron metal and oxygen was essentially completed within 48 hours.

The amount of dissolved oxygen replenished by each addition of new water to replace the water lost during sampling is about 6.6 mg. The oxygenation of iron with 6.6 mg dissolved oxygen (0.23 mg/l) would utilize about 11.5 mg of iron (or 0.4 mg/l Fe(II)). Water analysis of dissolved iron concentration showed negligible increases in most water samples. Only a few water samples from the steel loop system No. 3 exhibited the presence of dissolved iron. The results suggest that the hydrated iron oxide was being deposited on pipe walls.

Evidence of other modes of oxygen utilization in pipe loop system are difficult to ascertain. The enumeration of bacterial plate count develops only the population of microorganisms that can grow under a specified cultural condition. The microbiological analysis of loop water also recovers only a fraction of the overall microbial populations that may exist in pipe loop systems.

In this experiment with reduced recirculation velocity, a smaller variation in iron concentration was observed. The average iron concentration was 0.02 mg/l and 0.04 mg/l for filtered and unfiltered influent water, respectively. The average iron concentrations of water in the four loop systems (1, 2, 3 and 4) were 0.04, 0.04, 0.09 and 0.04 mg/l. The low iron concentrations observed indicated that most of the oxidized iron remained attached to the pipe walls. Observations through the clear PVC pipe sections connected to the steel pipe loop systems showed increasing amounts of accumulated sediment, including reddish-brown hydrated iron oxide

precipitates.

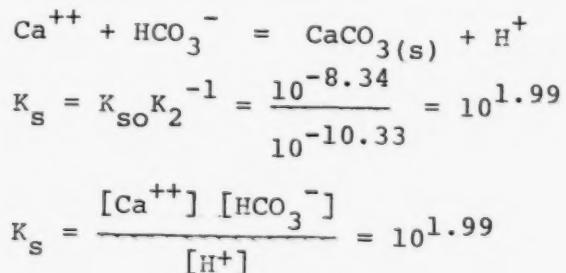
The variation in sulfate ion concentrations was not appreciable. The data indicated a slight decrease in the sulfate ion concentrations when the water temperatures were about 32°C - 35°C.

Microbiological analyses showed the presence of sulfate-reducing microorganisms in all of the pipe loop systems. However, the organism concentration in loop water was less than 10 organisms per ml of water. The detection of sulfate-reducing organisms was more frequent in water samples from the steel pipe loop systems than from the PVC pipe loop systems.

Very little measurable hydrogen sulfide was observed. After three weeks, less than 20 parts per billion of dissolved sulfide was found in the PVC and the steel pipe water. It is possible that sulfides could have reacted with iron and became deposited on pipe surfaces. Even if sulfides were being formed by microorganisms, the loop water analysis of dissolved sulfides did not show a significant level of microbial activities.

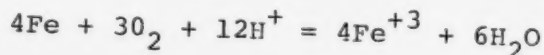
The analyses for alkalinity and total hardness are shown in Figure 33 for the four pipe loop systems. An initial reduction was observed for both alkalinity and total hardness in all loop systems. Thereafter, the water from the two PVC loop systems exhibited relatively constant values for alkalinity and hardness. In contrast, as before, the steel loop systems continued to show a further reduction of alkalinity and hardness with time. The reduction in alkalinity and hardness may be attributed to the precipitation of ferrous carbonate and calcium carbonate at pipe surfaces.

The extent of the precipitation reaction can be estimated by considering the equilibrium constants. The precipitation of calcium carbonate may occur by the following reaction between calcium and bicarbonate ions (93):



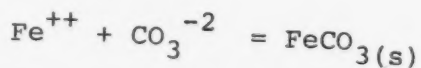
The analyses of pipe loop water quality were pH 7.8, 5 meq/l alkalinity and 4.8 meq/l hardness.

Under the experimental conditions calcium carbonate could precipitate only if hydrogen ion concentrations were as low as 10^{-9} moles/l. This requirement of low hydrogen ion concentrations could be developed if the following iron oxidation reaction was in progress at pipe surfaces.



The consumption of three mole equivalents of hydrogen ions per mole equivalent of iron metal would result in substantial decreases in hydrogen ion concentrations near the vicinity of iron oxidation. Consequently, at a limited pipe surface, conditions would be conducive to the precipitation of calcium carbonate.

Likewise, the precipitation of ferrous carbonate is possible if the product of Fe^{++} and CO_3^{-2} is greater than $K_{\text{so}} = 10^{-10.4}$ at 25°C .



When sections of steel pipes were examined, pipe surfaces exhibited localized corrosion and the occurrence of tubercles.

Thus, in steel pipe systems the oxidation of iron metal at steel pipe surfaces had induced the precipitation of calcium carbonate. The resultant water quality changes were decreases in alkalinity and hardness.

Other water quality parameters examined were pH, ammonium ion, phosphate and total organic carbon in loop water. Very little ammonium ion, phosphate and total organic carbon were observed. The pH of loop water did not change appreciably in any loop systems.

The University of Missouri-Columbia tap water contains exceptionally small amounts of organic carbon, generally lower than most distilled water sources. The total organic carbon as measured by a low-level TOC analyzer was 0.46, 0.50, 0.48 and 0.79 mg/l for water from loops No. 1-4 respectively after 60 days. The total organic carbon value of the influent water was 0.33 mg/l and 0.50 mg/l for the filtered and unfiltered tap water. The TOC of the loop water from the systems No. 1 and 3 after 180 days of study was 0.74 and 1.00 mg/l respectively. If one would assume that the increase in TOC were

attributable to the suspended organism growths, increases of 0.30 mg/l and 0.2 mg/l TOC in loops No. 3 and No. 4 would yield increases of 8.4 mg and 5.9 mg carbon, respectively.

$$0.3 \text{ mg/l} \times 28 \text{ l} = 8.4 \text{ mg carbon}$$

$$0.21 \text{ mg/l} \times 28 \text{ l} = 5.88 \text{ mg carbon}$$

Assume that the dry weight of one bacterium is 10^{-10} mg, the equivalent increase

$$\text{Loop No. 3: } \frac{8.4 \text{ mg}}{10^{-10} \text{ mg/org.}} = 8.4 \times 10^{10} \text{ org. (or } 3.0 \times 10^6 \text{ org./ml)}$$

$$\text{Loop No. 4: } \frac{5.88 \text{ mg}}{10^{-10} \text{ mg/org.}} = 5.88 \times 10^{10} \text{ org. (or } 2.1 \times 10^6 \text{ org./ml)}$$

of suspended organism concentration would be 3 million and 2.1 million organisms per ml of water in loop No. 3 and 4, respectively.

Although the tap water contained less than 1 mg/l of total organic carbon, it appeared to be capable of supporting a significant number of microorganisms in the loop systems.

Following disinfection and filtration, the bacterial plate counts of loop water samples showed no colonies after 48 hours incubation. However, the same plates, which were incubated at lower temperatures (20°C-25°C) for an additional four to six days, revealed a group of microorganisms. Since plate counts after two days incubation were generally low, the use of an extended incubation periods of eight days was followed when enumerating microbial concentration of loop water samples.

It is evident that the lower incubation temperatures (20°C-25°C) are more closely related to the actual water temperatures which the microorganisms are more accustomed to. Alternatively, it might be that the lower temperatures may be a prerequisite to better viability of indigenous microbial populations and artificially enriched laboratory media, such as the plate count medium.

The microbial enumeration on standard method agar media showed higher bacterial plate counts with extended incubation time and at lower growth temperatures.

Figure 34 shows the bacterial plate counts after eight days incubation period at 20°C-25°C. The initial plate count for water from the disinfected and filtered system was two orders of magnitude lower than that from the parallel system without any pretreatment. Within a few days plate counts from the disinfected pipe loop systems showed an increase of two to three orders of magnitude of microorganisms per ml sample. Results showed up to 5×10^5 organisms per ml in the PVC pipe loop system. In general, plate counts of water from the steel pipe systems were not as high as those from the PVC pipe systems. Plate counts of water from steel pipe systems reached $10^3 - 10^4$ organisms per ml.

A number of isolates were randomly selected from plate count media to subculture into pure culture forms. The lists of these isolates are summarized in Table 61. Many isolates which appeared on plate count media could not be subcultured into pure culture form because they failed to grow on plate count media upon subculturing. A number of other cultural media were examined to determine better growth media for subculturing. Table 61 indicates growth efficiency on various cultural media for the isolates that were selected from plate count media. In general, these isolates represent the organisms which were frequently observed in enumeration plates of test loop water.

These isolates were examined by an API 20E identification method in an effort to identify them. Results indicated that many of the isolates showed no reaction after 48 hours at 35°C. Therefore, definitive identifications were not possible.

The following groups of microorganisms were examined by means of selective enrichment culture media: iron-precipitating organisms, nitrifying and denitrifying organisms, nitrogen-fixing organisms, sulfur-oxidizing organisms and sulfate-reducing organisms.

After three weeks iron-precipitating organisms and sulfate-reducing organisms were observed in all loop water samples. Then sulfur-oxidizing/precipitating organisms were detected in loop Nos. 1 and 3. Occasionally, nitrifying and nitrogen-fixing organisms were detected in test loop water from pipe loop systems, Nos. 1, 3 and 4. Both denitrifying organisms and stalk-producing organisms were detected in all loop systems. Presence of these organisms were confirmed when pipe sediments from four pipe loop systems were also examined.

The importance of detecting these different group of microorganisms in loop water was that metabolic activities of a variety of microorganisms could combine to establish microbiotic

Table 61 Bacterial Cultures Isolated from the Pipe Loop System Water

Morphology of Cells Grown on Plate Count Media	Pigment on Plate Count Media	Gram Reaction	Oxidase Reaction	Mac Conkey Agar	Half Diluted Tryptone Glucose Agar	Trypticase Soy Agar	Basal Mineral Medium with Sucrose	Ferric Ammonium Citrate	Motility
1) Pleomorphic Rods	Yellow	-	-	-	+	+	++	+	+
2) Ellipsoid Rods	NP	-	-	-	++	+	-	+	-
3) Cocci	Yellow	+	-	-	++	+	+	+	-
4) Thick Rods	Pink	V	-	-	++	+	+	+	+
5) Thin Rods	Yellow	-	+	-	++	+	-	+	+
6) Yeasts	NP	-	-	-	++	+	+	+	-
7) Coryneform Rods	NP	V	-	-	++	+	-	+	+
8) Curved Rods	NP	+	-	-	+	-	-	-	+
9) Short Rods	NP	-	+	-	+	+	-	+	+
10) Coryneform Rods	NP	V	+	+	+	+	-	+	+
11) Rods	NP	-	+	-	+	+	+	-	-
12) Tapered and Curved Rods	NP	-	+	-	++	-	+	-	-
NP	No pigment		++	Good growth					
V	Variable		+	Fair growth					
			+	Scanty growth					
			+	Suppressed growth					
			-	No growth					

Table 61 Bacterial Cultures Isolated from the Pipe Loop System Water (con't)

Morphology of Cells Grown on Plate Count Media	Pigment on Plate Count Media	Gram Reaction	Oxidase Reaction	Mac Conkey	Agar	Half Diluted Tryptone Glucose Agar	Trypticase	Soy Agar	Basal Mineral Medium with Sucrose	Ferric Ammonium Citrate	Motility
13) Rods	NP	-	+	-	-	++	++	++	+	++	+
14) Thin Rods	NP	-	+	-	-	++	++	++	-	-	+
15) Thin, Curved Rods	Yellow(old) Orange	-	+	+	+	++	++	++	-	-	+
16) Rods	Yellow	-	+	+	+	++	++	++	+	++	+
17) Rods	NP	-	-	-	-	+	+	-	+	-	-
18) Tapered Rods	NP Yellow(old)	-	+	+	+	++	++	++	++	+	+
19) Rods	Yellow	-	+	-	-	++	++	++	-	-	+
20) Cocci bacilli to Rods	Yellow	-	-	-	-	++	++	+	++	++	+
	NP	No pigment			++	Good growth					
	V	Variable			++	Fair growth					
					+	Scanty growth					
					+	Suppressed growth					
					-	No growth					

Table 61 Bacterial Cultures Isolated from the Pipe Loop System Water (con't)

Morphology of Cells Grown on Plate Count Media	Pigment on Plate Count Media	Gram Reaction	Oxidase Reaction	Mac Conkey Agar	Half Diluted Tryptone Glucose Agar	Trypticase Soy Agar	Basal Mineral Medium with Sucrose	Ferric Ammonium Citrate	Motility
21) Rods	NP	-	-	+	++	+	-	+	+
22) Very small Rods	Orange	-	-	+	++	+	-	+	+
23) Thick Rods	Red	-	-	+	+	+	+	+	+
24) Very small Rods	NP	-	-	-	++	+	-	-	+
25) Rods	Yellow NP	-	+	-	++	+	-	-	+
26) Polymorphic Rods	(old) Yellow	V	-	-	+	+	+	-	-
27) Small Curved Rods	NP	-	-	-	+	+	-	+	-
	NP	No pigment		+++	Good growth				
	V	Variable		++	Fair growth				
				+	Scanty growth				
				+	Suppressed growth				
				-	No growth				

cycles of essential elements such as carbon, nitrogen, sulfur, iron, phosphorous, etc. A microbial ecosystem could be established with time which could potentially influence the concentrations of numerous constituents in water. Consequently, water quality changes may be attributed to microbial activities in water.

D. Pipe Loop Study No. 3: Utilizing Untreated Tap Water

A study employing the pipe loop system was conducted using a 1.52 m per second recirculation velocity, but without any pretreatment of the influent water. All of the loop systems were simply flushed with tap water before the water was added. The objective of this experiment was to confirm the previously observed changes in dissolved oxygen, iron and other water quality parameters. The experimental procedures were the same as those employed in the previous experiment.

The results of the observed water quality changes in the pipe loop systems are presented in Table 62. As observed previously, there were variations in the initial water quality within 48 hours. During the experiment water temperatures varied between 23°C - 28°C. Figure 35 shows the changes in dissolved oxygen concentrations. As in previous experiments the dissolved oxygen was initially reduced in all of the pipe loop systems. Up to 6 mg/l of oxygen was utilized when the first water sample was taken after 72 hours in the steel loop systems, whereas only 2 mg/l of oxygen reduction was observed in the PVC loop system during the same period.

The total iron concentrations of loop water samples from all pipe loop systems were negligible. It is evident, that oxidation of iron and hydrolysis of oxidized iron had completed soon after test menstrum was added into the pipe loop systems. Subsequent deposition of corrosion products resulted in minimal concentration of iron in pipe loop water.

The initial changes in the dissolved oxygen and dissolved total iron concentrations were essentially comparable to the previous two experiments. The elimination of chlorination as pretreatment and membrane filtration of influent water did not effect these observed water quality changes, i.e., the dissolved oxygen and iron concentrations in loop water.

Again, in this study, the net increase in bacterial plate counts was observed during the first 72 hours of the experiment.

Thereafter, the magnitude of bacterial plate counts fluctuated between 10^3 to 10^5 per ml of loop water.

Table 62 Results of Water Quality Changes in Pipe Loop Systems

Expt. Time hrs.	Loop System	pH	Dissolved Oxygen, mg/l	Total Iron, mg/l	Alkalinity meq/l	Hardness, as CaCO ₃ mg/l	Sulfate, mg/l	Plate Count, No./ml	Detection of Sulfate- Reducers
0	Tap	7.8	7.0	0.01	4.96	244	34	2.0x10 ³	-
72	No. 1	7.8	5.3	0.06	4.92	226	33	1.8x10 ⁴	-
	No. 2	7.8	4.7	0.01	4.80	222	31	6.1x10 ³	-
	No. 3	7.7	1.3	0.02	3.94	178	30	5.7x10 ³	-
	No. 4	7.8	1.1	0.02	4.12	196	30	3.7x10 ⁴	+
245	No. 1	7.7	6.0	0.07	4.74	228	32	1.0x10 ⁵	+
	No. 2	7.6	5.9	0.01	4.76	231	33	6.3x10 ³	-
	No. 3	7.8	1.4	0.01	3.82	181	30	3.3x10 ⁴	+
	No. 4	7.8	0.8	0.02	4.10	192	30	4.3x10 ⁴	+
310	No. 1	7.5	6.3	0.01	4.56	226	32	1.9x10 ⁴	+
	No. 2	7.7	6.0	0.01	4.72	118	34	2.1x10 ⁴	+
	No. 3	7.9	1.2	0.03	3.72	180	29	3.7x10 ³	+
	No. 4	7.9	1.1	0.01	4.04	196	30	3.5x10 ⁴	+
461	No. 1	7.8	4.3	0.02	4.56	220	32	1.8x10 ⁴	+
	No. 2	7.6	6.2	0.01	4.64	226	34	2.2x10 ⁴	-
	No. 3	7.7	1.2	0.05	3.60	172	29	2.0x10 ³	+
	No. 4	7.7	1.1	0.02	3.96	188	30	3.1x10 ⁴	-
741	No. 1	7.9	4.4	0.23	4.64	229	33	1.5x10 ⁴	+
	No. 2	7.8	6.0	0.01	4.76	230	33	1.6x10 ³	-
	No. 3	7.8	1.5	0.01	3.70	179	30	6.0x10 ³	+
	No. 4	7.7	1.4	0.01	4.18	196	30	3.0x10 ³	+

(Experimental Period: July 28, 1978 - August 28, 1978)

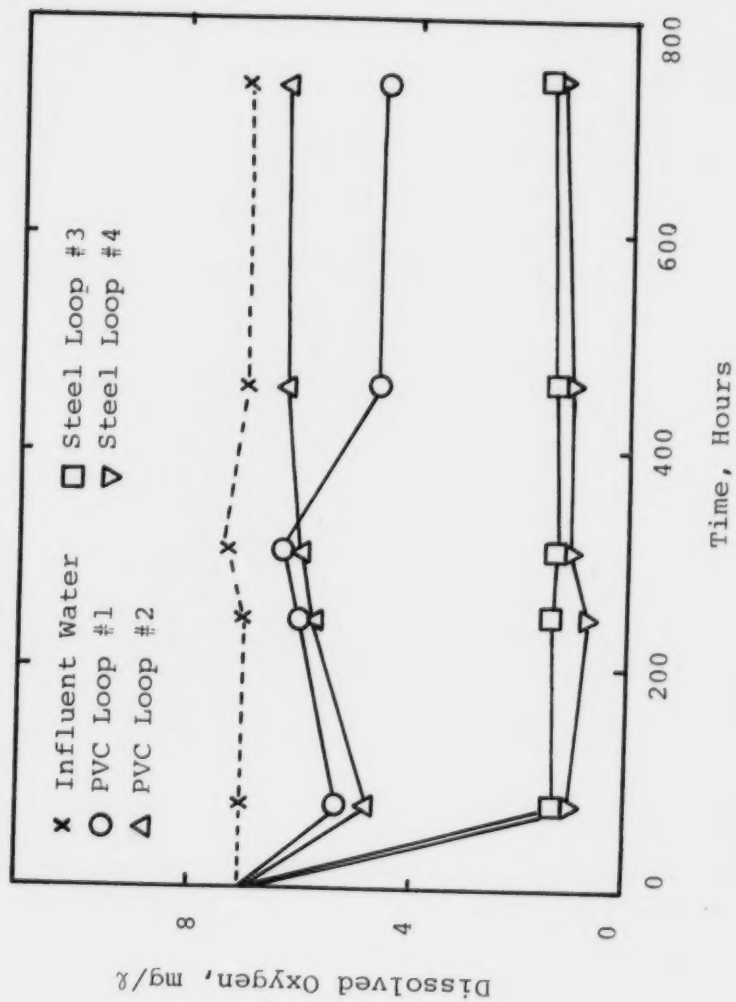


Fig. 35 Dissolved Oxygen in Pipe Loop System Water (July 28 - August 28, 1978)

During this experiment the sulfate-reducing organisms were detected more frequently in analyzed loop water samples than those in the previous two experiments. Up to 10^2 sulfate-reducing organisms per ml of water were found in water samples collected from the PVC loop system No. 1. The relative importance of the microbial activities of sulfate-reducing organisms was difficult to ascertain from this study. Moreover, the variations in sulfate ion concentrations were not appreciable.

As in two previous experiments, decreases in alkalinity and hardness of water from steel loop systems were evident. This experiment confirmed the previously observed water quality changes, including dissolved oxygen concentrations, iron concentration, alkalinity and hardness.

E. Pipe Loop Study No. 4: Influence of Sulfate-Reducing Organisms

The experiment was conducted to determine if the sulfate-reducing organisms could be grown in sufficient concentrations to affect the water quality changes in pipe loop systems. The influent pipe loop water were not pretreated before the experiment. About 10^6 sulfate-reducing organisms were inoculated into each pipe loop system, Nos. 1 and 3. After two days up to 10^3 sulfate-reducing organisms per ml of loop water were detected in loop systems Nos. 1 and 3. However, for most of the experimental period, less than one sulfate-reducing organism per ml of loop water was observed in both the PVC and the steel loop system.

The results of water quality analysis of two pipe loop systems Nos. 1 and 3 are presented in Table 63. The initial depletion of dissolved oxygen was comparable to the previous experiments (Figure 36). The experimental period of this study was not as long as in the previous experiments; however, difference in net changes in dissolved oxygen concentrations was observed in PVC loop system No. 1. The dissolved oxygen concentrations of water in the PVC loop system No. 1 had continually decreased with time. After 361 hours, the reduction of dissolved oxygen concentrations was 4.2 mg/l (117.6 mg oxygen) in PVC loop system No. 1. This increased amount of dissolved oxygen decrease in water was attributed to the oxygenation of iron. During this experimental period the water temperature ranged between 25°C - 28°C . Similarly, the iron concentration of water from PVC loop No. 1 increased to 0.46 mg/l after 361 hours.

The analysis of cast iron test specimens examined after 361 hours also revealed increased corrosion of test specimens (discussed in Chapter 7).

Table 63 Results of Water Quality Analyses of Pipe Loop Systems

Expt. Time hrs.	Loop System	pH	Dissolved Oxygen mg/l	Total Iron mg/l	Alkalinity meq/l	Sulfate mg/l	Plate Count mg/l	Detection of Sulfate- Reducing Org.
0	Tap	7.8	6.2	0.03	4.8	35	4.0×10^3	-
24	No. 1	7.8	3.8	0.22	NM	34	3.6×10^4	+
	No. 2	7.8	6.5	0.40	NM	34	6.1×10^4	-
	No. 3	7.8	1.7	0.25	NM	34	1.8×10^4	+
	No. 4	7.8	2.0	0.28	NM	33	1.8×10^4	-
72	No. 1	7.7	5.7	0.04	4.4	35	1.0×10^4	+
	No. 2	7.8	7.4	0.02	NM	32	9.4×10^4	-
	No. 3	7.8	1.3	0.07	4.3	33	2.2×10^4	+
	No. 4	7.8	1.4	0.29	NM	32	1.7×10^4	-
145	No. 1	7.7	4.4	0.04	4.6	34	1.6×10^4	+
	No. 3	7.6	1.2	0.05	4.2	34	6.8×10^3	+
237	No. 1	7.8	4.1	0.13	4.5	36	1.1×10^4	+
	No. 3	7.8	1.5	0.02	4.3	33	4.0×10^3	+
361	No. 1	7.8	2.0	0.46	4.9	36	3.3×10^3	+
	No. 3	7.8	1.5	0.02	4.2	33	4.4×10^2	+

(Experimental Period: September 1978 - October 4, 1978)

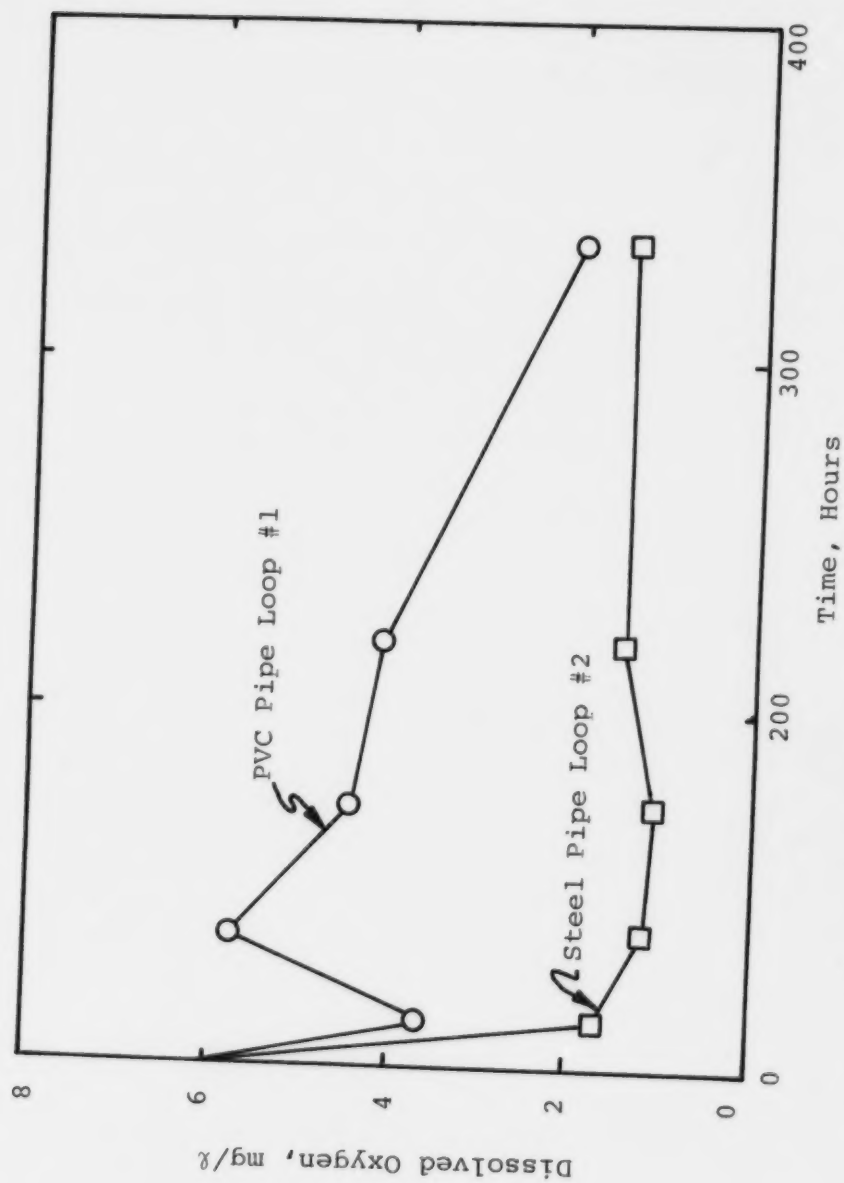


Fig. 36 Dissolved Oxygen in Pipe Loop System Water
(September 20 - October 4, 1978)

Other water quality parameters such as dissolved sulfide, sulfate ions, alkalinity, pH, and bacterial plate counts did not show any appreciable variations from previous experiments. Therefore, it was difficult to ascertain any effect of sulfate-reducing organisms from the observed analyses of loop water.

Further studies are warranted in order that their metabolic activities could be measured more accurately by some means other than the changes in sulfate and sulfide in solution or suspension.

Even if sulfides were formed by these organisms, the formation of metal sulfides and their deposition on pipe surfaces complicate the accurate assessment of sulfide production.

In conclusion, a number of observations related to water quality changes in pipe loop systems were derived from the four pipe loop studies.

- (1) The oxidation of iron metal was principally responsible for contributing iron to the water.
- (2) The oxygenation of iron results in the depletion of oxygen. In general, the major depletion of oxygen takes place immediately after the oxygenated water comes in contact with iron. Thereafter, the utilization of dissolved oxygen is minimal. In essence, the limited accessibility of oxygen to iron metal due to the formation of hydrated ferric oxide films on the metal surface caused reduced rate of iron oxidation. The role of "passive" activity by corrosion products was discussed in the literature survey.
- (3) Other parameters such as hydrogen ion concentration, alkalinity and hardness may be changed as a result of iron oxidation.
- (4) In general, the variations in concentrations of sulfate and dissolved sulfide in loop water were not appreciable. Thus, it was difficult to ascertain their importance as monitoring parameters of water quality changes. This observation does not necessarily imply that these water quality parameters are not important in monitoring water quality deterioration in distribution systems.
- (5) The total organic carbon concentration in water was important in estimating the potential capacity for

organisms growth in the pipe system. Since the test water contained exceptionally small amounts of total organic carbon, a relatively small amount of microbial activity was observed in the pipe loop systems.

- (6) The bacterial plate counts of water were low when microorganisms were enumerated according to the Standard Methods (95). Higher plate counts were obtained when the enumeration of organism were performed at lower temperatures and at an extended incubation period.
- (7) A variety of physiologically different populations of microorganisms was observed in the pipe loop systems as was observed earlier in Field Survey experiments. For instance, aerobic and facultatively anaerobic heterotrophs, autotrophic nitrifying organisms, denitrifying organisms, nitrogen-fixing organisms, iron-precipitating organisms, sulfate-reducing organisms, sulfur-oxidizing organisms and stalk-producing organisms were cultured. The cellular morphology of the observed microorganisms varied from cocci, bacilli, spirillum to pleomorphic forms. Their role in microbiotic cycles of elements such as carbon, nitrogen, sulfur, iron, etc., needs to be further evaluated.

SECTION 7

CORROSION STUDIES WITH THE SIMULATED PIPE LOOP SYSTEMS

INTRODUCTION

Although the fundamental principles of corrosion have been known for a long time, effective means of inhibiting corrosion have not been devised. When Iverson (102) traced the historical background of the microbial corrosion of iron, he cited Garrett (65) as the earliest investigator to have suggested that microorganisms might exert an influence on the corrosion of metals. Iverson stated that the initial role of bacterial corrosion was primarily related to the corrosion of pipes in the presence of oxygen. In most cases, tubercle formation by iron bacteria was postulated as a major cause of corrosion problems in water pipes.

In 1923, van Wolzagen Kuhr proposed that iron might be corroded in the absence of oxygen (68). The occurrence and mechanism of anaerobic biological corrosion was extensively examined by many investigators. However, the exact mechanism of anaerobic biological corrosion has yet to be resolved. Moreover, the effect of microbial growth on the corrosion rate of iron is still debatable because the extent of the biological activity within water mains has not yet been determined. Menzies (103) presented the five major mechanisms by which microorganisms may be involved in the corrosion process:

- (1) the production of corrosive metabolic products;
- (2) the production of differential aeration and concentration of cells;
- (3) depolarization of cathodic processes;
- (4) disruption of natural and other protective films;
- (5) the breakdown of corrosion inhibitors.

One objective of the present study was to evaluate the effects of microbial growth on the corrosion rate of the pipe materials, cast iron and steel.

By utilizing tap water as the test menstrum in a simulated pipe loop system, the study attempted to represent the internal pipe corrosion processes in a distribution system. Two methods of analyses were employed to evaluate the corrosion process:

- (1) Weight loss determinations were made on cast iron test specimens which were exposed to PVC pipe loop systems; and
- (2) Measurements were made of accumulated corrosion products, including microbial growth, within steel pipe loop systems.

Examination of the Corrosion of Cast Iron Test Specimens in PVC Pipe Loop Systems

A. Materials and Methods

To study the corrosion of cast iron specimens induced by the test water, the two PVC pipe loop systems were each equipped with six test specimen insertion sites. Either one or duplicate test specimens were inserted at each specimen insertion site. The specimen inserter was a 1 cm diameter teflon rod 46 cm long. A valve in the pipe loop system enabled the coupon to be removed and inserted without disturbing the experimental conditions.

The cast iron test specimens were cut from a pipe section removed from a distribution system. Each specimen was about 3.81 cm x 1.90 cm x 0.12 cm. The average exposed area of a test specimen was 13.99 sq. cm. The surface of a test specimen was milled to a high surface lustre. The specimen was soaked in acetone solution for about 10 minutes to remove oil and grease residues. The dried specimen was then weighed and sterilized by autoclaving.

When the PVC test loop system was filled with water, sterilized specimens were carefully inserted into PVC pipe systems. After a specified experimental period, test specimens were removed and scraped with a soft brush before immersing them into Clark's solution.

The basic method of corrosion analysis was the recommended practice described in the ASTM designation: G31-72 laboratory immersion corrosion testing of metals (104). Methods of cleaning corrosion products included both mechanical and chemical cleaning.

The effects of the chemical cleaner, Clark's solution (HCL, 1 liter, antimony trioxide 20g, stannous chloride 50g), in removing corrosion products was established as follows. A "blank" specimen, one which had not been reacted in the test water previously, was weighed before and after immersion into the cleaning solution. About 0.3 percent weight loss was resulted when the "blank" specimen was exposed for about

40 minutes. The weight loss was about 0.03 percent when the exposure time was reduced to about five minutes. Moreover, visual observations revealed that the immersion of test specimens into the Clark's solution for about two minutes was adequate to remove all corrosion products. Therefore, it was decided that after a brief scraping with a soft brush, the test specimen would be immersed into the Clark's solution for three minutes to remove corrosion products.

The apparent rate of corrosion was calculated as described in the ASTM G31-72.

$$\text{Corrosion Rate (mdd)} = (K \times W) / (A \times T \times D)$$

where

K = constant ($2.40 \times 10^6 \times D$) for cast iron

T = time of exposure in hours to the nearest 0.01 hour

A = area in cm^2 to the nearest 0.01 cm^2

W = mass loss in gm, to the nearest 1 mg

D = density of metal in gm/cm^3 ; 7.20 g/cm^3 for carbon steel

mdd = mg per dm^2 per day

Corrosion of test specimen is reported in terms of corrosion intensity. Corrosion intensity is defined as mg of specimen weight loss per sq dm of exposed area.

The corrosion experiments were conducted during four experimental periods:

Experiment No. 1: June 2, 1978 - July 2, 1978

Experiment No. 2: June 14, 1978 - July 2, 1978

Experiment No. 3: July 28, 1978 - August 28, 1978

Experiment No. 4: September 19, 1978 - October 4, 1978

The water quality data from these studies have been reported in Section 6. The four experiments were conducted at average water recirculation rate of 1.42 m per second. Water temperatures during these experiments varied between 22°C - 35°C . Experiment No. 2 was conducted with the same test specimens which were employed in the previous experiment. The initial surface condition of these test specimens was

rougher textured than other test specimens.

B. Results and Discussion

Results of corrosion intensity data for experiment Nos. 1, 2, 3 and 4 are presented in Tables 64 through 67. As expected, the cumulative weight loss of test specimens increased with time.

Experiment No. 1 was conducted with water recirculating at a rate of 1.50 m per second. Water temperature varied between 22°C - 28°C. The corrosion intensity of the cast iron specimens with time is shown in Figure 37.

When test specimens were sterilized in the autoclave, a 2 mg weight loss per specimen was observed initially. Measurements made during the first 100 hours of exposure yielded data which were somewhat erratic, possibly due to the small weight losses being measured. As the exposure progressed, the corrosion intensity gradually decreased until it appeared to reach a steady-state, constant rate. A linear function $y = 0.02x + 2.95$ described the relationship between corrosion intensity and time after 100 hours of exposure. The correlation coefficient of the function with the data is 0.958. From these results the following observations were noted: (1) the test medium, tap water, is corrosive to cast iron test specimens; (2) the cast iron specimens corroded at a high rate initially; (3) an apparent steady-state rate of corrosion was observed after the first 100 hours of exposure.

Experiment No. 2 was performed under the same experimental conditions as the previous experiment. Water was recirculated at 1.5 m per second, and test specimens were inserted into each specimens insertion site after sterilizing in the autoclave. The test specimens were uneven, coarser-textured than those utilized in the previous experiment because they had been exposed to the test water previously. Corrosion intensity data for experiment No. 2 are presented in Table 65 and Figure 38. In this case, the data could best be described by a first order reaction function, $W_t = W(1 - e^{-K_2t})$, where W_t = weight loss at time t , W = weight loss at time infinite, t = time of exposure, and K_2 = rate constant of corrosion.

The analysis of data yielded a K_2 value of 0.16/day or 0.0067/hour. The weight loss of test specimens was significantly higher than those observed in the previous experiment. Differences up to 350 mg/dm² additional weight loss were observed utilizing the rough surfaced test specimens after 400 hours. Further experimentation may be warranted to confirm the effect of test specimen surface texture on corrosion intensity.

Experiment No. 3 was conducted to further evaluate the

Table 64 Corrosion Intensity of Cast Iron Test
Specimens in PVC Pipe Loop System

Loop No. & Position	Elapsed Time (Hours)	Weight Loss (mg)	Corrosion Intensity (mg/dm ²)	Bacterial Plate Count (No./ml)
I - 5	24	38.6	276	3.05×10^4
II - 2	28	54.8	392	2.40×10^4
I - 6	48	56.0	400	9.60×10^4
II - 5	54	80.5	576	6.20×10^4
I - 2	63	39.4	282	1.16×10^5
II - 1	285	101.9	728	3.22×10^5
II - 6	285	121.6	869	3.22×10^5
I - 1A	308	136.7	977	1.90×10^5
I - 1B	308	118.7	848	1.90×10^5
II - 1A	308	117.6	841	1.60×10^5
II - 1B	308	114.6	819	1.60×10^5
II - 2A	317	125.4	896	1.60×10^5
II - 2B	317	124.0	886	1.60×10^5
II - 3A	330	123.5	883	9.40×10^4
II - 3B	330	122.9	878	9.40×10^4
I - 2A	336	131.7	941	1.40×10^5
I - 2B	336	152.8	1092	1.40×10^5
I - 4A	377	149.1	1066	7.80×10^4
I - 4B	377	138.3	989	7.80×10^4
II - 4A	382	154.9	1107	8.00×10^4
II - 4B	382	189.8	1357	8.00×10^4
I - 5A	436	151.7	1084	2.00×10^5
I - 5B	436	186.7	1334	2.00×10^5
II - 5A	436	163.6	1169	8.00×10^4
II - 5B	436	180.0	1287	8.00×10^4
I - 3A	722	239.5	1712	1.00×10^5
I - 3B	722	231.4	1654	1.00×10^5

Experimental Period: April 15 - 27, 1978

June 2 - July 2, 1978

Table 65 Corrosion Intensity of Cast Iron Test
Specimens in a PVC Pipe Loop System

Loop No. & Position	Elapsed Time (Hours)	Weight Loss (mg)	Corrosion Intensity (mg/dm ²)	Bacterial Plate Count (No./ml)
II - 1	1	6.0	43	1.0×10^2
		5.9	42	
II - 1	10	36.2	259	1.0×10^3
		35.8	256	
II - 1	31	57.8	413	9.0×10^4
		54.0	386	
II - 1	99	102.5	733	8.0×10^4
		108.3	774	
II - 2	99	98.9	707	2.0×10^5
		112.8	806	
II - 3	384	176.7	1263	3.9×10^5
		233.4	1668	
II - 4	453	207.1	1480	4.9×10^5
		201.4	1440	

Recirculation Rate of Water: 1.5 mps

Experimental Period: June 14, 1978 - July 2, 1978

Water Temperature: 22°C - 28°C

Coupon surface was rough since coupons were the same as those used in Experiment No. 1.

Table 66 Corrosion Intensity of Cast Iron Test
Specimens in PVC Pipe Loop System

Loop No. & Position	Elapsed Time (Hours)	Weight Loss (mg)	Corrosion Intensity (mg/dm ²)	Bacterial Plate Count (No./ml)
I - 1	72	65.8	470	4.8×10^4
II - 1	72	101.1	726	9.4×10^4
I - 5	245	104.5	747	1.8×10^5
II - 5	245	89.3	638	6.3×10^4
I - 2	310	106.7	763	1.9×10^4
II - 2	310	109.1	780	2.1×10^4
I - 3	355	130.6	936	2.4×10^4
II - 3	355	115.8	828	1.5×10^4
I - 4	461	139.2	995	4.1×10^4
II - 4	461	137.2	981	8.4×10^4
I - 6	741	194.7	1392	1.5×10^4
II - 6	741	180.8	1292	1.6×10^4

Loop I Recirculation Rate: 1.46 m per second

Loop II Recirculation Rate: 1.37 m per second

Experimental Period: July 28 - August 28, 1978

Table 67 Corrosion Intensity of Cast Iron Test
Specimens in PVC Pipe Loop System
(with Sulfate-Reducing Organisms)

Loop No. & Position	Elapsed Time (Hours)	Weight Loss (mg)	Corrosion Intensity (mg/dm ²)	Bacterial Plate Count (No./ml)
I - 1	72	65.8	470	4.8×10^4
II - 1	72	101.1	726	9.4×10^4
I - 5	245	104.5	747	1.8×10^5
II - 5	245	89.3	638	6.3×10^4
I - 2	310	106.7	763	1.9×10^4
II - 2	310	109.1	780	2.1×10^4
I - 3	355	130.6	936	2.4×10^4
II - 3	355	115.8	828	1.5×10^4
I - 4	461	139.2	995	4.1×10^4
II - 4	461	137.2	981	8.4×10^4
I - 6	741	194.7	1392	1.5×10^4
II - 6	741	180.8	1292	1.6×10^4

Pipe Loop No. 1: 1.43 feet per second

Experimental Period: September 19, 1978 -
October 4, 1978

Table 67. Corrosion Intensity of Cast Iron Test
Specimens in PVC Pipe Loop System
(with Sulfate-Reducing Organisms)

Loop No. & Position	Elapsed Time (Hours)	Weight Loss (mg)	Corrosion Intensity (mg/dm ²)	Bacterial Plate Count (No./ml)
I - 1	72	65.8	470	4.8×10^4
II - 1	72	101.1	726	9.4×10^4
I - 3	245	104.5	747	1.8×10^5
II - 5	245	89.3	638	6.3×10^4
I - 2	310	106.7	763	1.9×10^4
II - 2	310	109.1	780	2.1×10^4
I - 3	355	130.6	936	2.4×10^4
II - 3	355	115.8	828	1.5×10^4
I - 4	461	139.2	995	4.1×10^4
II - 4	461	137.2	981	8.4×10^4
I - 6	741	194.7	1392	1.5×10^4
II - 6	741	180.8	1292	1.6×10^4

Pipe Loop No. 1: 1.43 feet per second

Experimental Period: September 19, 1978 -
October 4, 1978

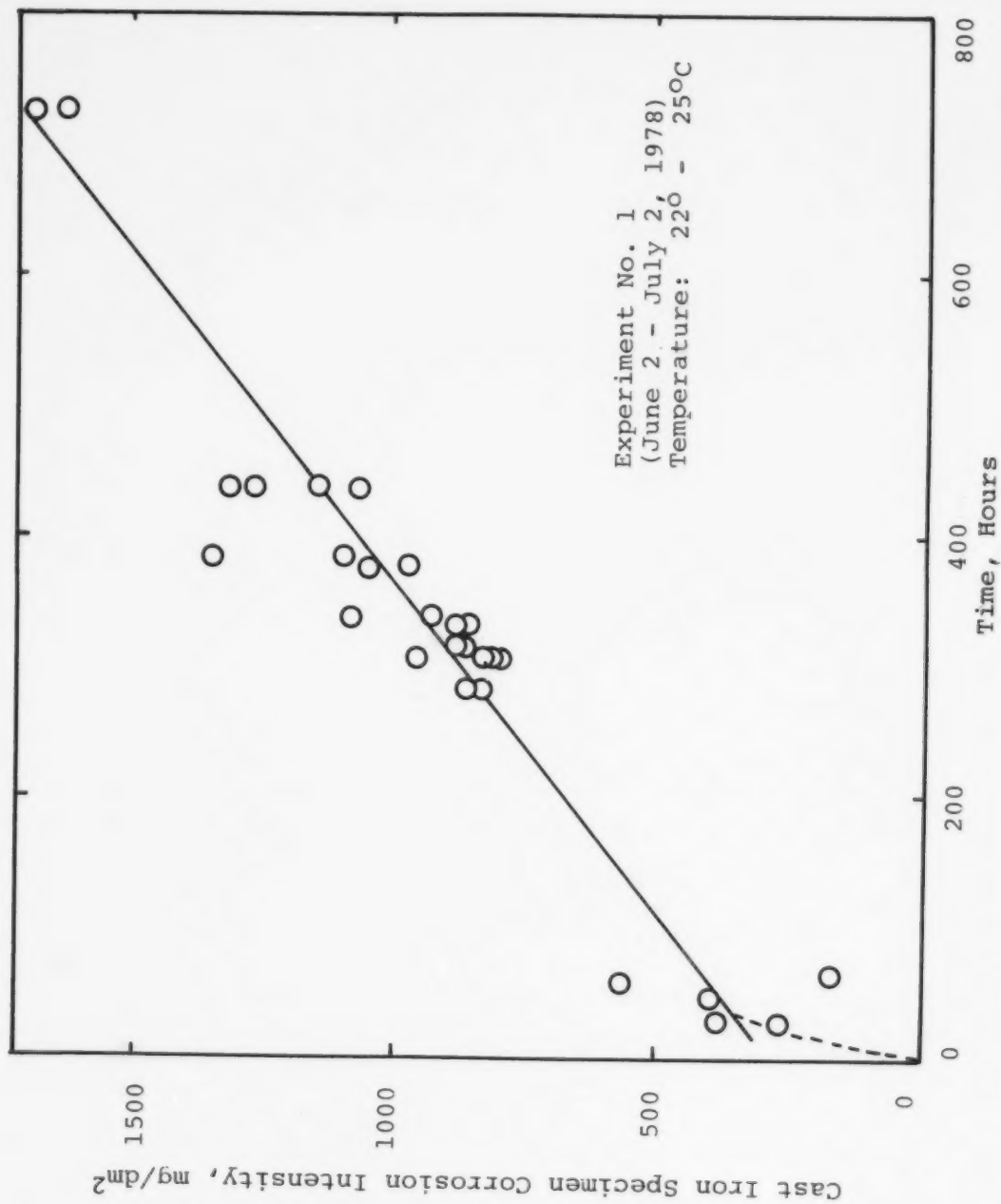


Fig. 37 Corrosion Intensity of Cast Iron Specimens in a PVC Pipe Loop System

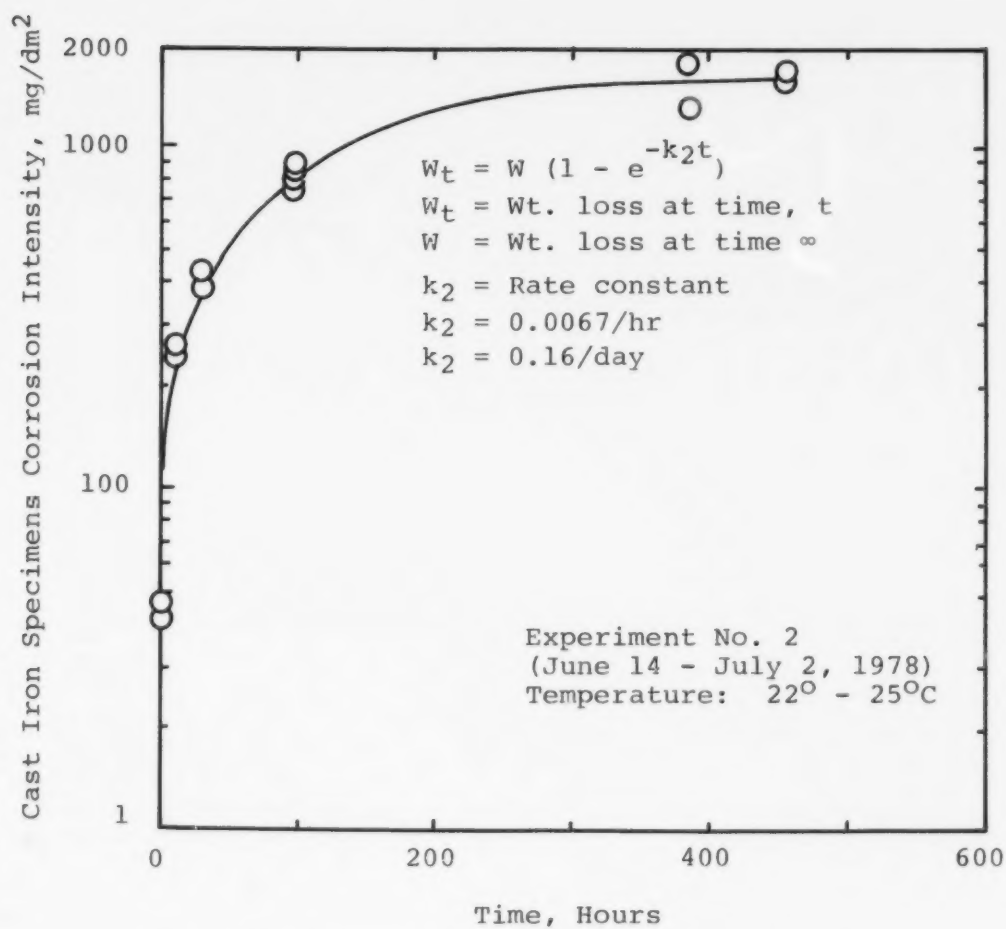


Fig. 38 Corrosion Intensity of Cast Iron Specimens in a PVC Pipe Loop System

corrosion intensity of cast iron specimens in the PVC pipe loop systems. In this experiment test specimens were inserted into the PVC pipe loop system when the water quality was at a steady-state (constant quality) condition. The PVC test system water was not replenished with fresh tap water initially. The loop water had less dissolved oxygen (6.9 mg/l), small amounts of total dissolved iron, and consistently high bacterial concentrations. The data on corrosion intensity (mg/dm²) are indicated in Table 66 and are shown in Figure 39. Corrosion intensity after 100 hours may be expressed with a linear regression equation, $y = 0.01x + 4.56$, where y is corrosion intensity and x is the corrosion test period in hours. The correlation coefficient of function for corrosion intensity with the observed data was 0.95.

The corrosion intensity of specimens tested under the conditions of experiment No. 3 was only slightly less than that observed in experiment No. 1. Therefore, it appears that the initial water quality did not have a significant effect on the observed corrosion intensities. In fact, the two experiments seem to have replicated fairly well, tending to confirm the validity of the experimental apparatus and procedures.

Experiment No. 4 was initially designed to study the effect of sulfate-reducing organisms in PVC pipe loop system. Two weeks prior to experiment No. 4, sulfate-reducing organisms were inoculated into the test loop system. Test specimens were inserted into the system to evaluate the effect of microbial growth, in particular, the growth of sulfate-reducing organisms, on the corrosion intensity of cast iron specimens. The resulting data are presented in Table 67.

Although a slight difference in the corrosion intensity of test specimens was observed, the difference could not be definitely attributed to the growth of sulfate-reducing organisms in the system because the concentration of the organisms in the loop water remained minimal. When test specimens were removed from the PVC pipe loop systems, the corrosion products were dark brown to black in color. The previous test specimens had rusty colored corrosion products. This difference in the corrosion products of test specimens may have resulted from the formation of iron sulfide. Since the loop water did not yield any significant concentrations of the seeded organisms, it was assumed that the activity of these organisms in the loop water remained low.

Since the corrosion intensity of the test specimens in all four experiments did not appear to show any major significant differences, the results of these experiments were compiled and plotted together (Figure 40).

As expected, the corrosion intensity increased with time.

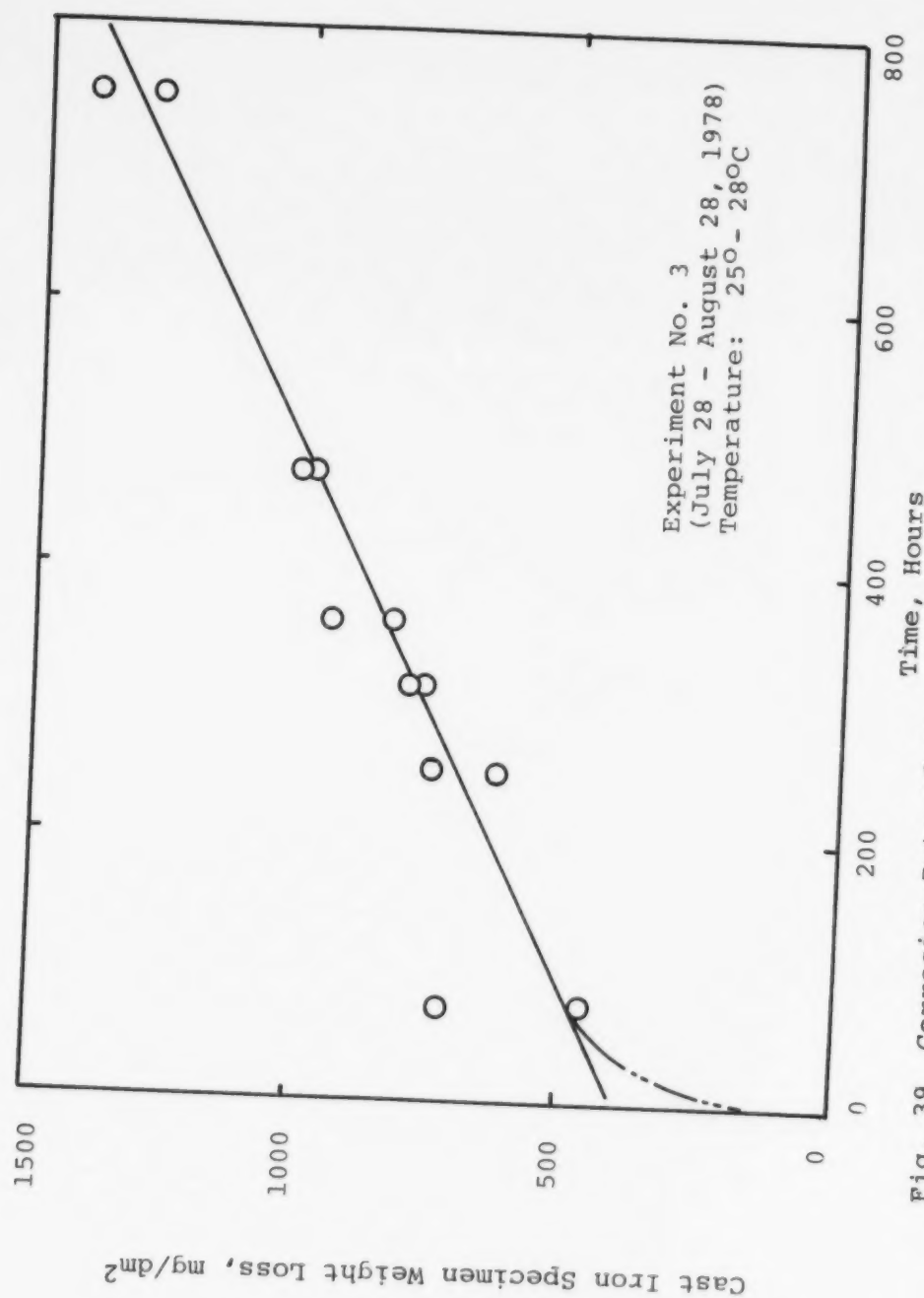


Fig. 39 Corrosion Rate of Cast Iron Specimens in a PVC Pipe Loop System

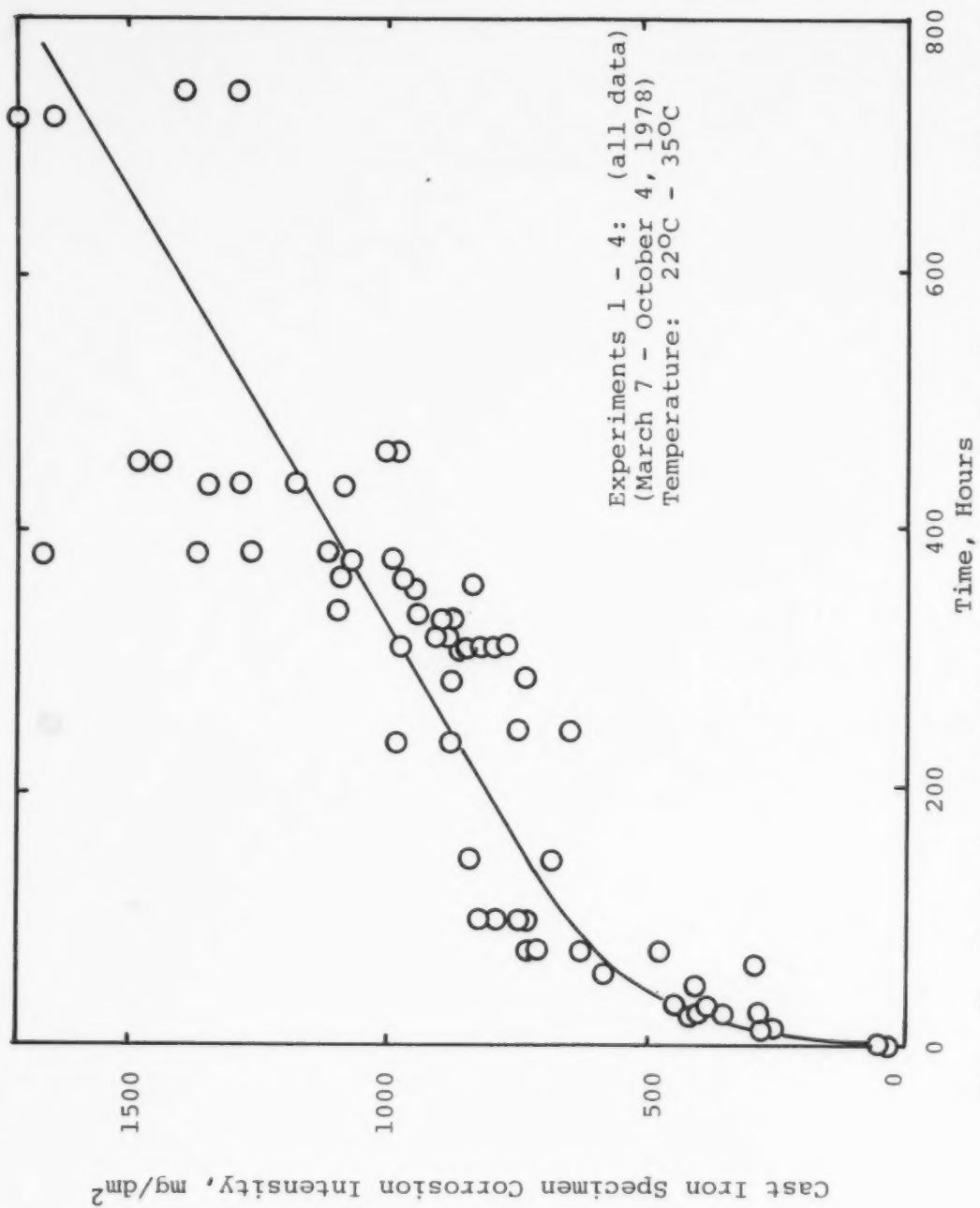


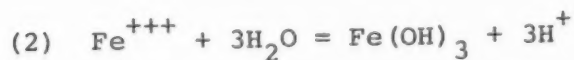
Fig. 40 Corrosion Intensity of Cast Iron Specimens in a PVC Pipe Loop System

At first, the rate of weight loss increased sharply, then decreased with time until it reached a constant rate.

The observed results may indicate that the rate of corrosion may be related to the dissolved oxygen content of water, i.e., when the oxygen utilization is initially high, the test specimen corrosion rate is also high. The corrosion rate thereafter remains relatively constant when the dissolved oxygen concentration and other water quality parameters in the water remain relatively unchanged.

When iron corrodes in aqueous solution, the ferrous iron formed can react with dissolved oxygen in water and produce hydrated ferric iron oxides. It has been shown on numerous instances that these oxides can exert passivation, i.e., suppress corrosion by decreasing oxygen diffusion to metal. A complete passivation can stop the corrosion process completely. Since a lower, steady-state, rate of corrosion was still observed in the present study, it may be that ferric hydroxide provided only a partial passivation. The density of ferric oxide is 3.7 - 3.9, while the density of iron metal (Fe^0) is 7.8. When iron corrodes and forms oxides, it would cover metal surface, but there would still be more uncorroded metal surface. Thus, the corrosion of this unreacted iron could be subjected to a diffusion limited oxygen concentrations. Thus, the steady-state corrosion rate may be largely dependent upon the efficiency of oxygen diffusion through the ferric oxide layer.

When corrosion of cast iron is dependent mainly on dissolved oxygen, the oxidation of iron may proceed according to these reactions:



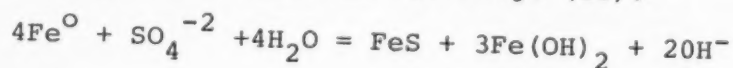
The reaction (1) combines the initial oxidation of iron ($\text{Fe}^0 = \text{Fe}^{++} + 2\bar{\text{e}}$) and further oxidation of iron (II) to iron (III). The reaction (2) represents the subsequent hydrolysis of iron ions to form hydrated ferric oxides. The oxidation of iron can occur at some distance from the metal surface provided that electrons penetrate the initially formed ferric oxide layer. Thus, the oxygenation of ferrous ions might continue to progress even after the production of ferric oxides on metal surface.

If one assumes these chemical reactions obey the molar ratio specified above, the iron to oxygen (mass/mass) ratio from reaction (2) is 2.3.

Results from the current study indicate that about 2 mg/l of dissolved oxygen, (a total of 56 mg of oxygen) was utilized during the first few days. About 129 mg of iron could have been corroded with the available oxygen. When test specimens were examined, about 50 mg of weight loss per test specimen was observed. Since 6 to 12 test specimens were inserted initially during each experiment, 300 to 600 mg total iron had reacted. This amount is 2-5 fold higher than would be expected from the oxidation of iron by available oxygen (129 mg Fe). The additional reaction of iron may have been induced by biological activity.

Microbiological analysis of test specimen corrosion products showed the presence of organisms that were also found in loop water analysis. The presence of sulfate-reducing organisms was confirmed in scrapings of some of the test specimens.

Although the water analysis of loop water yielded only a slight decrease (2-5 mg/l) in sulfate ion concentrations, one might relate iron oxidation with sulfate reduction using the following overall corrosion reaction, originally proposed by von Wolzogen Kuhr and Van der Vlugt (68).



From this equation the ratio of iron to sulfate (mass/mass) is calculated to be 2.3. If 2-5 mg/l sulfate ions (the total of 56-140 mg of sulfate) were involved in the corrosion of iron, a total of about 129-322 of iron might be oxidized.

No direct studies were performed to determine the growth rate of sulfate-reducing organisms in pipe loop systems. In general, less than 10 organisms were found per 10 ml of water samples. Mara and Williams (105) found that the bacterial growth rate to be an important factor in the corrosion processes. He had observed at dilution rate, $D = 0.024$ per day, the ratio of iron Fe corroded to FeS produced (mg/mole) to be 23.40, while at $D = 2.36$ per day the iron sulfide ratio was 1.65. Since these authors did not quantify the bacterial growth yield nor the steady-state bacterial concentration in their reactor systems, insufficient information is available to judge whether the metabolic activities of sulfate-reducing organisms (i.e., the total of 2.8×10^3 - 2.8×10^4 organisms per loop systems) could be responsible for 129 - 322 mg of iron oxidation.

Evaluation of Pipe Corrosion by Analysis of Corrosion Products

When iron or steel metal corrodes, various corrosion products are formed, including hydrated ferric oxide, ferrous

oxide, ferrous carbonate, etc., Camp and Meserve (82) indicated these precipitates and others including calcium carbonate, magnesium carbonate, magnesium phosphate as a result of the corrosion of iron in fresh water. Most probably, similar reactions may also dominate in corrosion of iron or steel pipes in distribution systems. The extent of corrosion can be determined either by measuring the amount of metal loss or the rate of formation of corrosion products.

To determine the extent and nature of pipe corrosion, accumulated pipe deposits were analyzed with respect to time.

A. Materials and Methods

The UMC laboratory tap water was used as the test menstrum. Two steel pipe systems, each consisting of six removable pipe sections, 30 cm in length, and two PVC pipe systems, also containing two removable pipe sections, were used. In the steel pipe systems, three test pipe sections were made of PVC pipe, while the other test pipe sections were made of steel pipe. The purpose of inserting the PVC test pipe sections into the steel pipe system was to enable visual examination of the pipe accumulations which were either transported to or precipitated at the PVC pipe surface within the steel pipe system. Each test pipe section was connected to an adjoining pipe with a threaded union and valve so that the test section could be removed after each test period. The sampling locations for both the PVC and steel pipe loop systems are shown in Figure 41 .

Pipe deposits were collected into sterile, phosphate-buffered, saline solution. A sterilized rubber plunger was used to dislodge the sediments from the pipe wall. Fifty ml of suspension was analyzed to determine the amount of total volatile and fixed solids. Methods specified in Standard Methods (95) for residue analysis were employed. Microbiological analysis included bacterial plate counts and the evaluation of various microbial population in sediments. The same procedure was employed as used for water analysis.

B. Results and Discussion

The results of pipe deposit analyses are summarized in Table 68 . PVC pipe system No. 2 and steel pipe system No. 4 had received an intermittent pretreatment process, chlorination, while pipe system No. 1 and No. 3 did not. It was assumed that the deposits observed in the PVC pipe systems were derived from the corrosion products from the cast iron specimens, while the deposits observed in the steel pipe systems were derived from the steel pipe metal. As expected, more accumulation was observed in the steel pipe systems than the PVC pipe systems. Moreover, within the steel pipe system more deposits were observed in steel test pipe section than in PVC test pipe section. For example, within the steel loop system

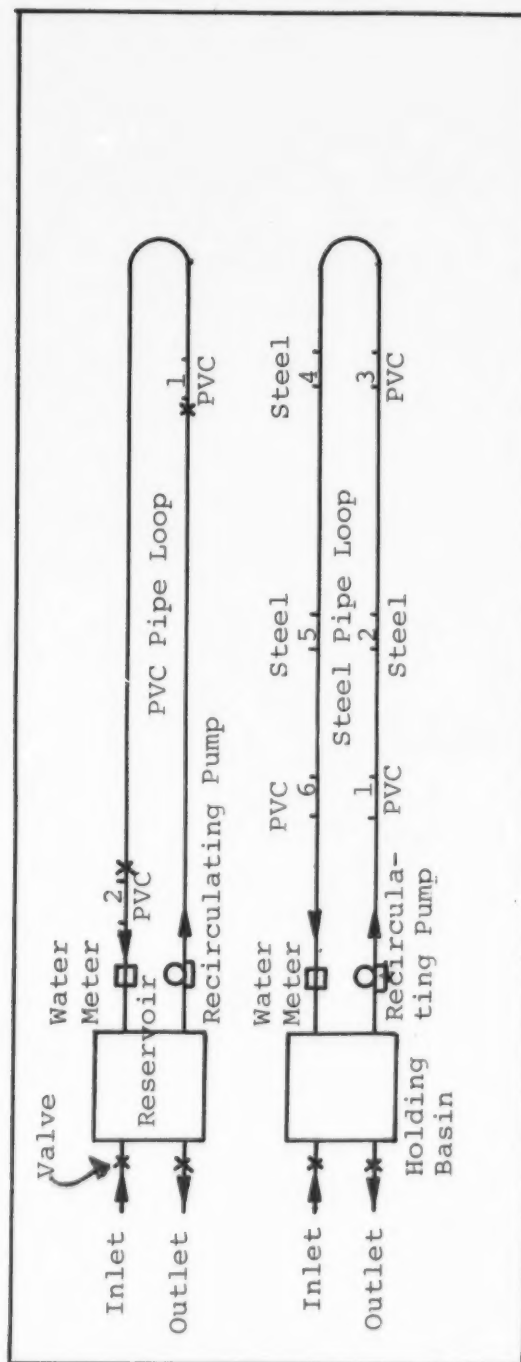


Fig. 41 Sampling Locations and Removable Pipe Sections in PVC and Steel Pipe Loops

Table 68 Analyses of Pipe Depositions from Pipe Loop Systems

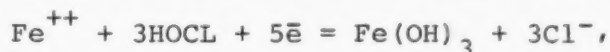
Pipe System No. - Type	Exp't Duration (days)	Total Solids (mg/ft.pipe)	Volatile Solids (mg/ft.pipe)	Percent Volatile Solids(%)	Organism per Test Section (org./ft.pipe)	Organism per Unit area ₂ (org./cm ²)
<u>PVC Pipe Loop System No. 1</u>						
1 - PVC	150	55.9	5.8	10.38	3.78×10^7	2.45×10^5
2 - PVC	150	78.9	6.0	7.60	3.66×10^7	2.38×10^5
<u>Steel Pipe Loop System No. 3</u>						
1 - PVC	180	133.8	13.1	9.79	4.49×10^7	2.92×10^5
2 - Steel	330	741.2	69.3	9.35	1.75×10^8	1.14×10^6
3 - PVC	180	135.7	11.8	8.70	5.28×10^7	3.43×10^5
4 - Steel	210	388.7	33.5	8.62	9.70×10^7	6.30×10^5
5 - Steel	260	481.8	46.4	9.63	1.23×10^8	7.99×10^5
6 - PVC	180	126.1	10.4	8.25	4.65×10^7	3.02×10^5

Table 68 Analyses of Pipe Depositions from Pipe Loop Systems (con't)

Pipe System No. - Type	Exp't Duration (days)	Total Solids (mg/ft. pipe)	Volatile Solids (mg/ft. pipe)	Percent Volatile Solids(%)	Organism per Test Section (org./ft. pipe)	Organism per Unit area (org./cm ²)
<u>PVC Pipe Loop System No. 2</u>						
1 - PVC	60	14.0	-	-	1.36×10^3	8.96
2 - PVC	60	20.0	-	-	3.52×10^3	22.90
1 - PVC	150	160.9	67.0	41.64	1.21×10^7	7.86×10^4
<u>Steel Pipe Loop System No. 4</u>						
1 - PVC	80	65.4	1.5	2.29	4.96×10^7	3.22×10^5
1 - PVC	150	145.7	49.2	33.77	1.92×10^3	12.47
2 - Steel	80	177.2	11.2	6.32	3.18×10^7	2.06×10^5
2 - Steel	240	678.2	141.5	20.86	7.93×10^7	5.15×10^5
3 - PVC	210	308.4	21.5	6.97	2.32×10^6	1.49×10^4
4 - Steel	330	707.2	59.8	8.46	2.71×10^6	1.76×10^4
5 - Steel	120	311.5	34.7	11.14	8.49×10^5	5.51×10^3
5 - Steel	210	537.0	125.8	23.43	1.29×10^7	8.38×10^4
6 - PVC	80	63.2	2.0	3.16	2.54×10^7	1.65×10^5
6 - PVC	150	128.6	36.8	28.62	4.53×10^5	2.94×10^3

No. 4 the amount of deposits accumulated on the PVC pipe at the position 3 after 210 days of experiment was 308 mg, while the amount of deposits on the steel pipe at the position 5 was 537 mg. The difference was more striking because while the PVC pipe deposits contained only 21.5 mg of volatile solids, the steel pipe had 125.8 mg volatile solids during the same period.

Analyses of total and fixed solids on test pipes are shown in Figures 42 and 43. In general, an increasing amount of solids was deposited with time. A greater amount of deposits was observed in the steel pipe system No. 4 as compared with the system No. 3. This may be attributed to the periodic chlorination of steel pipe system No. 4. The introduction of chlorine may stimulate another cathodic reaction,



and contribute to additional $\text{Fe}(\text{OH})_3$ formation. As a result, the total accumulated deposits in steel pipe system No. 4 may be expected to be higher.

The pipe deposits were found to contain volatile solids which ranged from 2.3 percent to 41.6 percent. The results of the analysis for percent volatile solids in pipe deposits are plotted in Figure 44. In general, the volatile solids in the pipe sediment increased with time. As the exposure time progressed, the bacterial concentration increased in decreasing rate. Since the amount of total solids increased steadily with time, the percent volatile solids decreased to 10-20 percent range.

After 80 days, a relatively constant population of microorganisms was observed in pipe sediments. This would imply that the microbial growth was not dependent upon the quantities of deposits on the pipe surface. Presumably, the minimal concentration of organic substance (i.e. TOC 0.5 mg/l) present in the test water, could support about $10^7 - 10^8$ viable organisms in the sediments of 30 cm (1 ft) of pipe.

If one would convert the amount of viable microorganisms in each pipe loop system to organic cell mass measurement as mg of dry cell mass, it would be about 1.0 mg per pipe loop system. This value is negligible in comparison to the experimental values (mg biomass) obtained from the measurement for volatile solids in pipe sediments.

It might be that the organic carbon in test water could have contributed to the volatile solid measurements. If one assumes that 0.5 mg/l total organic carbon are present in test water, possibly 14 mg (28 l x 0.5 mg/l) of organic carbon might

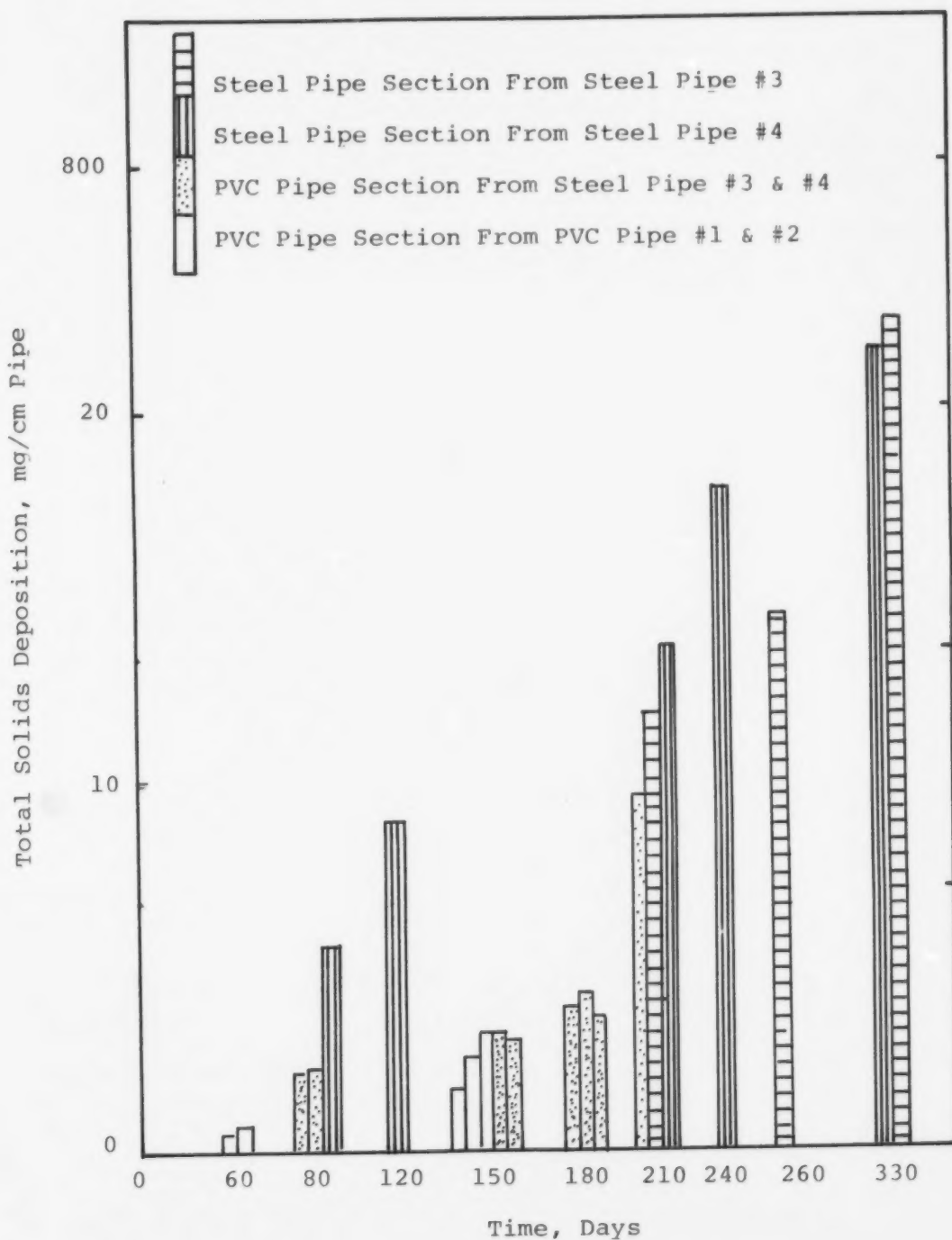


Fig. 42 Total Accumulated Solids in Removable Pipe Sections

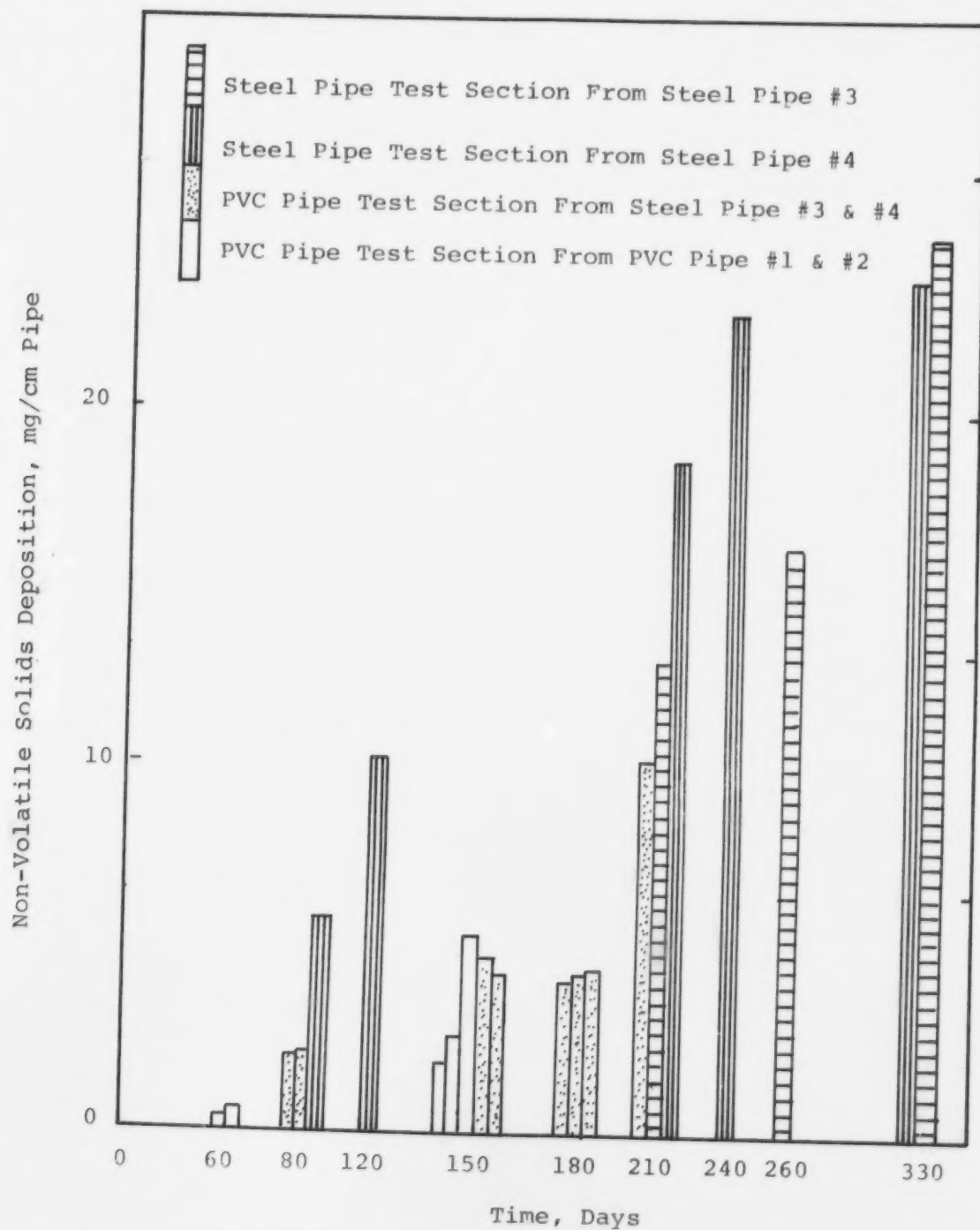


Fig. 43 Non-Volatile Solids Accumulation in Removable Pipe Sections

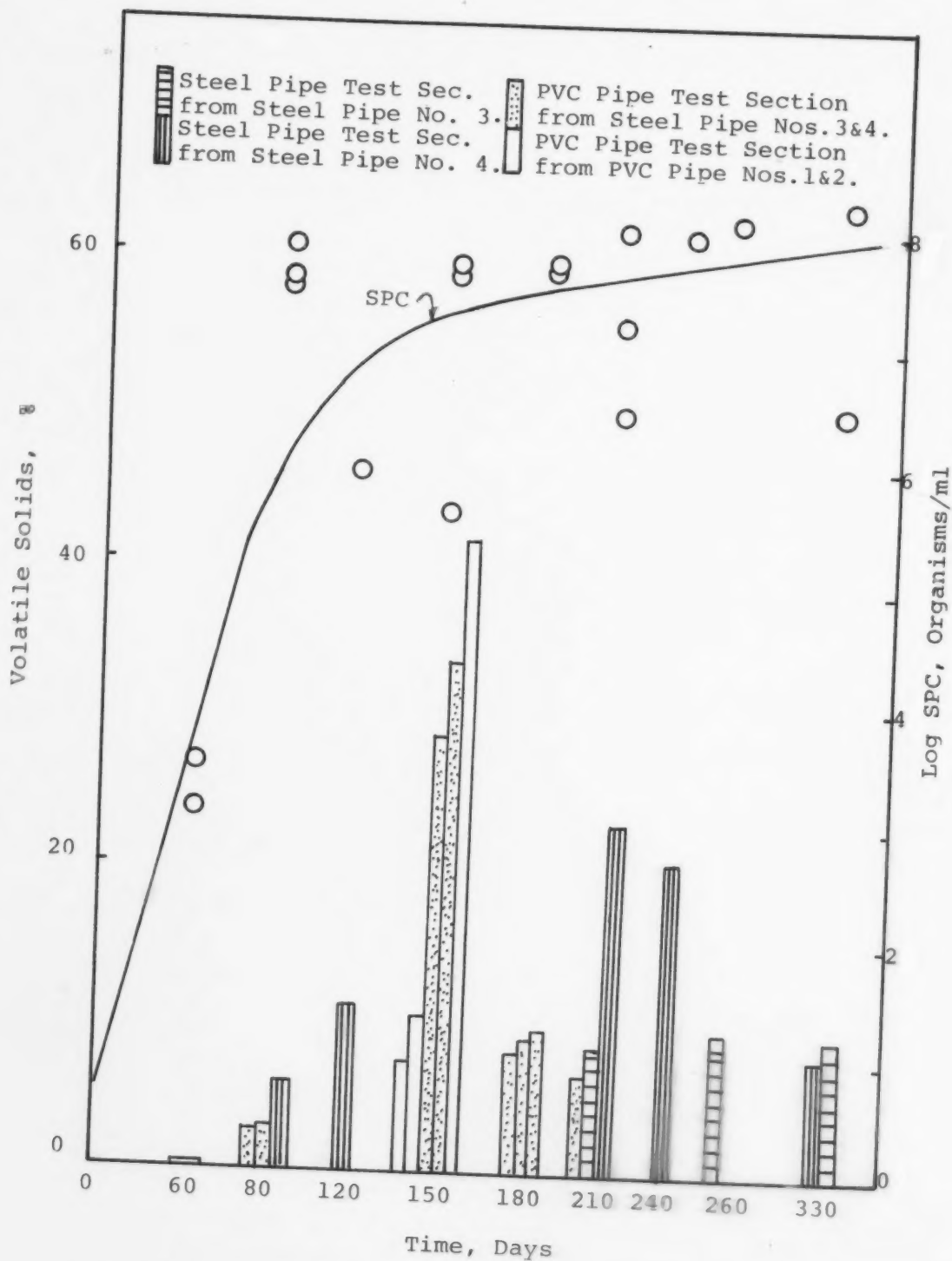


Fig. 44 Volatile Solids in Pipe Loop Deposits

be deposited on pipe surfaces. Since five percent of water is exchanged per sampling time, the detention time of the entire water is 20 days. Over the experimental period, i.e., up to 330 days, presumably the maximum amount of organic carbon that can be deposited on pipe surfaces would be 230 mg.

Investigations were made of the presence of other groups of microorganisms in the pipe sediments. The results of these studies are given in Table 69 . The same group of microorganisms were also observed in pipe loop water analysis. The confirmation of detection of these group of microorganisms in both sediments and suspending water indicates that these organisms are part of indigenous microorganisms in drinking water. It may be reasonable to assume that the bacterial plate counts yield only a part of total indigenous microbial communities in pipe loop system ecology.

In conclusion, the evaluation of pipe sediment deposits delineated the formation of corrosion products as cast iron and steel test specimens were oxidized in oxygenated water. An increased amount of solids indicated an increased amount of iron oxidation with time. The rate of iron oxidation was difficult to ascertain since the test pipe sections that were analyzed were interconnected within a pipe loop system.

Attempts to relate bacterial growth to the observed volatile solids yielded insufficient data since only a small quantity of organic carbon could be accounted for from the viable cell counts.

Table 69 Results of Microbiological Analysis of Pipe Sediment

Pipe System No. - Type	Exp't Duration (days)	Sulfate Reducers	Sulfur Oxidizers	Nitrogen Fixers	Nitrifiers	Denitrifiers	Stalk-Prod. Organisms
PVC Pipe Loop System No. 1							
1 - PVC	180	+	+	+	-	+	+
2 - PVC	180	+	+	+	+	+	+
PVC Pipe Loop System No. 2							
1 - PVC	60	+	-	+	-	+	-
2 - PVC	60	-	-	+	-	+	-
Steel Pipe Loop System No. 3							
1 - PVC	180	+	+	+	+	+	+
2 - Steel	330	+	+	+	+	+	+
3 - PVC	180	+	+	+	+	+	+
4 - Steel	260	+	+	+	+	+	+
5 - Steel	330	+	+	+	+	+	+
6 - PVC	180	+	-	+	+	+	+
Steel Pipe Loop System No. 4							
1 - PVC	80	+	+	+	+	+	+
2 - Steel	80	+	+	+	+	+	+
3 - PVC	260	+	+	+	+	+	+
4 - Steel	330	+	+	+	+	+	+
5 - Steel	80	+	+	+	+	+	+
6 - PVC	80	-	+	+	+	+	+

+: Presence of Organism -: Absence of Organism

SECTION 8

BIOLOGICALLY MEDIATED CORROSION STUDIES IN BATCH REACTOR SYSTEMS

INTRODUCTION

Batch corrosion studies were performed with microorganisms isolated from pipe loop water to determine the effect of microbial growth on the corrosion of cast iron specimens. Initially, an experiment was conducted with pipe loop water supplemented with carbon and nitrogen sources. Thereafter, a number of single culture corrosion experiments were performed with organisms isolated from the pipe loop system. The objective of these experiments was to determine the influence of individual culture growth on the corrosion rate of cast iron. Finally, the influence of acclimated microbial biota from the pipe loop system on the corrosion rate of cast iron test specimens was evaluated.

Corrosion of Cast Iron Specimen Exposed to Sulfate-Reducing Organisms and Other Microorganisms in Pipe Loop System Water

The first experiment was conducted utilizing sulfate-reducing organisms and microorganisms established in test pipe loop water. The test menstrum was collected from the simulated pipe loop system and refrigerated at 4°C. until the start of the experiment. Sulfate-reducing organisms were grown in Baar's Reinforced medium for 5 days. When growth was indicated by the presence of a black ferrous sulfide precipitate, the supernatant was pipetted into a sterile centrifuge tube. The cell suspension was then centrifuged at 2,000 g for 15 minutes. The supernatant was decanted, and the centrifuged cells were resuspended with sterile phosphate buffer. The cell suspension was washed twice after which the cells were aseptically inoculated into the experimental bottles, No. 5 and 6. Four bottles served as controls for the experiment. One set (Bottles Nos. 1 and 2) contained sterilized loop water and the other (Bottle Nos. 3 and 4), non-sterilized loop water. Carbon in the form of sodium lactate (50 mg/l as carbon) and nitrogen in the form of ammonium chloride (10 mg/l as nitrogen) were added to Bottles No. 1, 3, and 5. Duplicate cast iron test specimens were included in each bottle.

Cast iron test specimens were degreased with an alcohol-acetone (1:1) solution and washed in soap and water. The surface dimensions and specimen weights were measured and recorded. The cast iron specimens were attached to a teflon rod which was fastened to the bottle cap. When all test specimens were attached to each of the experimental bottles, they were sterilized by autoclaving at 120°C for 20 minutes. The screw-capped culture bottles were used as the experimental test system. After the necessary constituents had been added to each bottle, the cast iron test specimens were resterilized by means of flame sterilization. The anaerobic environment in the bottles was achieved by completely filling the bottle with test menstium. The reaction bottles were agitated with a laboratory shaker to provide a constant motion of test menstium. The experiment was conducted for a seven day period.

The results of the chemical analysis of the water in contact with the test specimens, as well as the results of the enumeration of aerobic heterotrophs and the presence of sulfate-reducing organisms are presented in Table 70. The two control bottles that were sterilized prior to the experiment were contaminated with spore-forming organisms. The two bottles which received non-sterile loop water had predominantly yellow pigmented and non-pigmented rods. Observation of colonies on standard plate count media showed different predominant groups of microorganisms in each test system. Larger numbers of the fluorescent group, *Pseudomonas* sp., were observed in both bottles that had been inoculated with sulfate-reducing organisms.

Experimental bottle No. 5, which contained sulfate-reducing organisms and which had both carbon and nitrogen nutrient, showed a decrease of 65 percent in the concentration of sulfate ions. On the other hand, no significant sulfate ion reduction was observed in test system No. 6 in the absence of additional carbon and nitrogen sources. In the control systems (Bottles No. 1, 2, 3 and 4), the experimental systems to which carbon and nitrogen substances had been added, showed slightly more corrosion of the cast iron test specimens.

The initial study illustrated that the growth of sulfate-reducing organisms may influence the corrosion rate of cast iron specimens. The principal corrosion product on the test specimens in Bottle Nos. 1, 2, 3 and 4 was hydrated ferric oxide whereas the major corrosion product on the specimens in Bottle Nos. 5 and 6 was black iron sulfide.

The influence of the sulfate-reducing organisms on corrosion rate was further evaluated by the following two batch culture studies. Unlike the first experiment sulfate-reducing organisms were grown in culture medium in order that the

Table 70 Batch Studies of the Effect of Sulfate-Reducing Organisms on the Corrosion of Cast Iron Test Specimens in Pipe Loop Water

Bottle Number	Initial Condition	Weight Loss mg	Exposed Area cm ²	pH	Sulfate mg/l	Dissolved Fe mg/l	Total Fe mg/l	Aerobic Heterotrophs no./ml	Sulfate-Reducing Organism no./ml	Corrosion Intensity ng/dm ²
1	Sterilized water with C/N	15.4	23.8	8.2	37	2.9	0.01 44.7	5.0x10 ³	No	64.6
2	Sterilized water without C/N	11.0	24.0	8.0	36	4.8	0.01 37.2	1.2x10 ⁴	No	45.9
3	Non-sterile with C/N	16.0	24.3	7.8	36	2.8	0.01 55.5	2.5x10 ⁴	No	65.8
4	Non-sterile without C/N	10.8	24.5	7.7	35	2.3	0.01 38.0	2.4x10 ⁵	No	44.2
5	Non-sterile with C/N	20.7	23.9	7.8	14	1.5	0.03 53.5	10.0 2.6x10 ⁵	10 ⁷	86.8
6	Non-sterile without C/N	21.7	24.6	7.9	40	2.7	0.03 61.2	12.2 5.8x10 ⁵	10 ⁷	88.4

Test Systems Nos. 1 & 3: Sterilized & Non-sterilized Loop water with 50mg/l C and 10mg/l N, respectively.
 Test Systems Nos. 2 & 4: Sterilized and Non-sterilized Loop water without C and N sources, respectively.
 Test Systems Nos. 5 & 6: Both Non-sterilized Loop water, both inoculated with 10⁷/ml sulfate-reducing but with and without 50mg/l C and 10mg/l No, respectively.

*Analysis of sulfide in clear supernatant after settling
 Experimental Period: September 7 - 14, 1978

Temperature: 28°C - 30°C

bacterial growth may be examined. The effect of bacterial growth on the corrosion rate of cast iron was investigated.

The Effect of Sulfate-Reducing Organisms on the Corrosion Rate of Cast Iron

The sulfate-reducing organism, more specifically the anaerobic dissimilatory sulfate-reducing bacteria, are abundant in nature, and probably ubiquitous. It is a rare occurrence to take a soil or a polluted water sample in which these organisms cannot be found. Natural water, both fresh and salt-water, often contains sulfate-reducers. Generally, aquatic microorganisms tend to be physiologically adapted either to fresh-water or salt-water habitats but not both. However, most strains of the sulfate-reducing bacteria thus far isolated have been found readily adaptable between salt-free medium and that containing the sea-water concentration.

There are at least eight distinct species of sulfate-reducing organisms recognized today. Miller and Tiller (106) listed the sulfate-reducing bacteria and some of their characteristics. It is difficult to grow pure cultures of sulfate-reducing bacteria because of certain peculiarities of these organisms. For example, bacteria produce sulfide ions, which can react with the ferrous ions that have been incorporated into the growth medium, forming iron sulfide precipitates. Since a considerable number of bacteria can be embedded in these precipitates, population densities and growth rates are extremely difficult to determine. Consequently, a uniform standardized suspension of the bacteria is difficult to prepare even for an experienced worker.

Today, although pure cultures and refined techniques are available, much work still remains to be resolved in comparing the nutrition, physiology and biochemistry of these recognized species. Perhaps for these reasons, the relative contributions of and all the chemical processes by which these bacteria may be involved in inducing corrosion have not been ascertained. Even with electrochemical studies the electrodes may be poisoned by the sulfide so that readings may be unreliable.

The corrosion of iron in oxygen-free neutral environment has been associated with the activities of the sulfate-reducing bacteria (107). Since these organisms have been observed in pipe loop systems of previous experiments with pipe loop studies as well as water samples of a number of water distribution systems examined earlier, the present experiments were performed to determine the effect of these organisms on the corrosion rate of iron.

A. Materials and Methods

A culture of sulfate-reducing organisms was taken from the test pipe loop system. Inocula of sulfate-reducing organisms were prepared, as follows. The initial inoculum was from a pipe loop system. A loopful of supernatant culture with sulfate-reducing organisms was reinoculated into a sterile Baar's Reinforced liquid medium. After their growth was indicated by the appearance of black precipitates (iron sulfide), a cell suspension from the clear supernatant at the upper part of the medium was centrifuged and washed twice in sterile phosphate buffer. A microscopic examination of cell suspension was performed to verify its purity.

In the first experiment, the Baar's Reinforced liquid medium contained 500 mg/l ferrous ammonium sulfate (70 mg/l as Fe^{++}), whereas in the second experiment, a trace amount of ferrous ion was added into the experimental growth medium.

Cast iron test specimens were prepared as in the previous experiments.

Two sets of control bottles were utilized. One set (Bottle Nos. 1, 5, 8 and 10) contained sterilized tap water. Another set (Bottle Nos. 2, 3, 6 and 11) contained the sterilized medium. The test system set (Bottle Nos. 4, 7, 9 and 12) contained the medium plus the inoculated sulfate-reducing organisms. After several days one bottle from each set was taken from the shaker apparatus and the menstrum tested for Eh, pH, iron, hydrogen sulfide, sulfate, heterotrophic bacteria and sulfate-reducing organisms. The test specimen weight loss was measured after removal of the corrosion products with the Clark's solution. Corrosion intensity was determined in terms of mg/dm^2 .

In the second experiment ferrous ammonium sulfate was excluded from the Baar's Reinforced medium composition. Again, two sets of control bottles were utilized. One set (Bottle Nos. 1, 5, 8 and 11) contained the sterilized water with thioglycollate, and the other set (Bottle Nos. 2, 3, 6, 9 and 12) contained medium without the ferrous ions. Test system (Bottle Nos. 4, 7, 10 and 13) contained the medium plus the innoculated sulfate-reducing organisms.

An equivalent amount of sodium thioglycollate, a reducing agent, was added to the sterile water control bottles to obtain an oxidation-reduction potential (Eh) similar to that of the medium. After the water was sterilized, the Eh obtained by the addition of the reducing agent was found to be -95 mv, while that of the sterilized medium was -205 mv.

B. Results and Discussion

The results of the batch culture study with sulfate-reducing organisms grown in Baar's medium are presented in Table 71. The average corrosion intensity for the test specimens is presented in Figure 45. The data indicate a significantly greater weight loss for cast iron test specimens which were exposed to sulfate-reducing organisms grown in nutrient.

The average corrosion intensity of cast iron specimen was 360 mg/dm² for specimens exposed for 14 days. When test specimens were exposed for 22 days, the average corrosion intensity increased to 602 mg/dm². The growth of organisms was found to have increased to its maximum density at 14 days. Thereafter, the density of bacteria decreased. Perhaps the quantity of nutrients available and the conditions in the experimental bottle restricted the maximum growth of bacteria to 14 days.

The results of batch culture study inoculated with sulfate-reducing organisms in iron-deficient medium are summarized in Table 72. The corrosion intensity of cast iron test specimens exposed to sulfate-reducing organisms and the comparable control systems are presented in Figure 46. Both control systems without organism and experimental systems with organisms yielded increased corrosion rate in cast iron test specimens.

An anomalous result was observed in experimental bottle No. 13. Although 22 days of experimental period had elapsed, only 10³ sulfate-reducing organisms per ml of test menstrum was observed. The least amount of growth had resulted in low sulfide concentration (0.3 mg/l) in the supernatant of culture medium. Moreover, the corrosion intensity of cast iron test specimens exposed to the experimental condition of Bottle No. 13 had exhibited a rate similar to the control test specimens.

In the first experiment corrosion intensities in both control systems showed a decreased rate of corrosion with time in contrast with an increased rate of corrosion in the presence of sulfate-reducing organisms. Since experimental bottles were completely filled with test menstrum, the amount of dissolved oxygen available for iron oxidation was limited in control systems. Therefore, it would result in eventual cessation of corrosion with test specimens in control systems.

In the second experiment corrosion intensities in both control systems increased with time. When thioglycollate was added to the control water system, thioglycollate had exerted corrosive action on iron. The following series of reactions might have occurred in control water systems with thioglycollate.

Table 71 Batch Studies of the Effect of Sulfate-Reducing Organisms on the Corrosion of Cast Iron Test Specimens in Baar's Medium

Exp't Time Days	Bottle Number	Condition	Weight Loss mg	Exposed Area cm ²	Eh mv	pH	Dissolved Iron mg/l	Dissolved Sulfide mg/l	Sulfate- Reducing Org. Conc. no./ml	Corrosion Intensity mg/dm ²
5	1	sterile	7.8	25.3	-400	5.8	NM	0.03	0	30.8
		water only								
	2	nutrient only	6.5	25.4	-330	6.4	NM	0.17	0	25.6
	3	nutrient only	8.0	26.8	-280	6.5	NM	0.14	0	29.8
4	4	nutrient plus organism	11.6	26.3	-288	6.6	NM	100	10 ⁴	44.2
11 261	5	sterile	8.5	25.2	-260	6.4	NM	0.03	0	33.8
		water only								
	6	nutrient only	15.4	25.4	-290	6.7	NM	NM	0 ⁷	60.6
	7	nutrient plus organism	32.7	24.9	-379	NM	1.08	165	10 ⁷	131.2
14	8	sterile	6.7	26.5	-230	6.4	NM	NM	0	25.3
		water only								
	9	nutrient plus organism	91.1	25.3	-420	6.6	1.05	183	10 ⁹	360.3
22	10	sterile	-0.7	25.4	-254	NM	NM	NM	0	0
		water only								
	11	nutrient only	7.8	25.5	-312	6.4	NM	NM	0 ⁶	30.6
	12	nutrient plus organism	153.2	25.4	-384	6.5	1.75	185	10 ⁶	602.5

Temperature - 25° - 28°C

NM - Not Measured

Initial pH of water 7.7

Initial pH of nutrient - 7.6

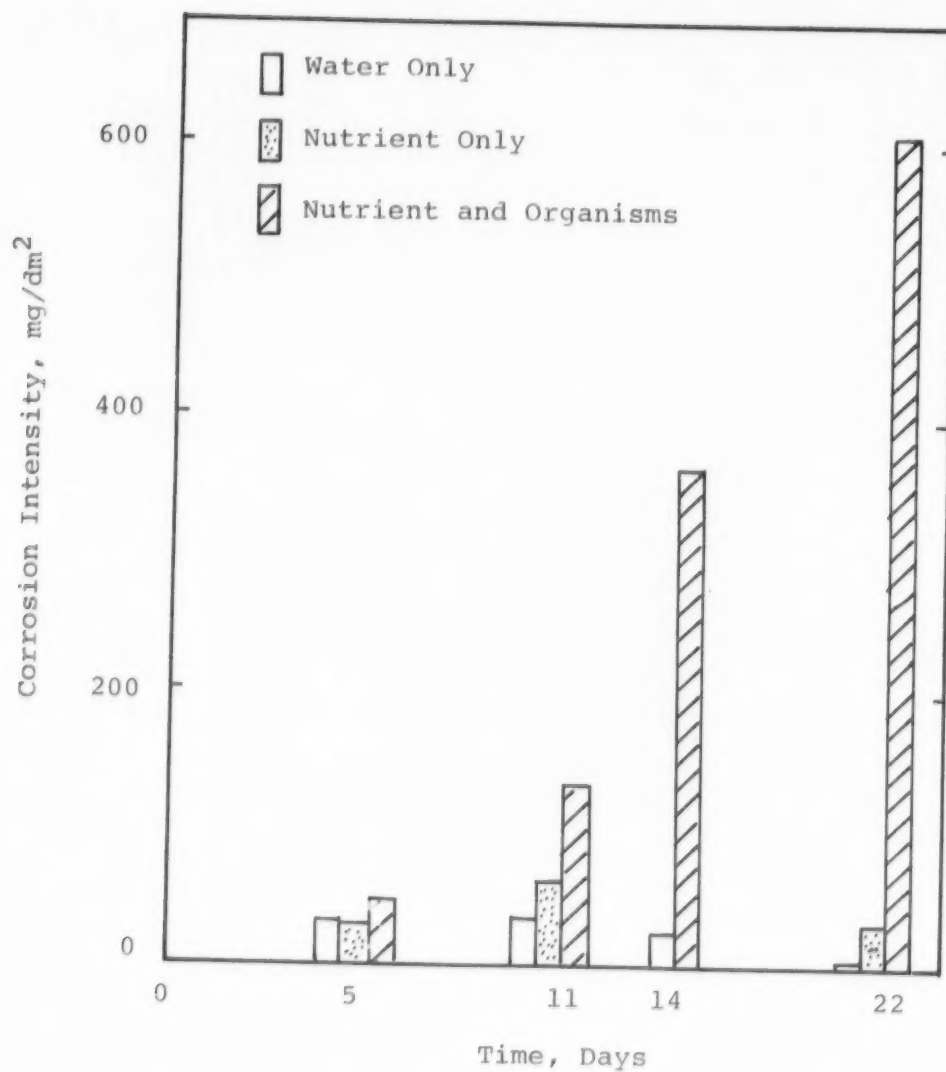


Fig. 45 Corrosion Intensity of Cast Iron Specimens Exposed to Sulfate-Reducing Organisms Grown in Baar's Medium

Table 72 Batch Studies of the Effect of Sulfate-Reducing Organisms on the Corrosion of Cast Iron Test Specimens in Baar's Medium without Ferrous Ammonium Sulfate

Elapsed Time Days	Bottle Number	Experimental Conditions	Weight Loss mg	Exposed Area cm ²	Eh mv	pH	Dissolved Fe mg/l	S ²⁻ mg/l	Conc. of Sulfate-Reducing Organism no./ml	Specimen Weight Loss mg/cm ²
0	1	Water*	-	-	-95	6.8	-	-	-	-
	2	Nutrient**	-	-	-205	6.8	-	-	-	-
1	3	Nutrient	0.7	24.3	-205	6.8	NM	0	0	2.9
	4	Organism***	0.2	25.4	-	6.7	NM	0	10 ⁴	0.8
7	5	Water	17.8	24.4	-465	NM	NM	0		73.0
	6	Nutrient	14.8	25.2	-278	NM	NM	0		58.7
	7	Organism	23.5	25.3	-380	NM	2.2	0	10 ⁷	92.9
11	8	Water	23.7	24.3	-472	8.2	NM	0		97.5
	9	Nutrient	28.9	25.2	-289	6.5	NM	0		114.7
	10	Organism	70.7	25.5	-369	6.6	2.6	157.5	10 ⁹	277.2
22	11	Water	60.4	24.3	-479	8.3	5.8	0.1		248.6
	12	Nutrient	62.8	25.7	-306	6.4	7.0	0.1		244.4
	13	Organism	56.3	25.3	-397	6.5	2.6	0.3	10 ³	222.5

* Water & Thioglycollate Temperature: 22°C - 25°C
 ** Nutrient Only
 *** Nutrient plus Organisms
 Experimental Period: August 11 - September 2, 1978

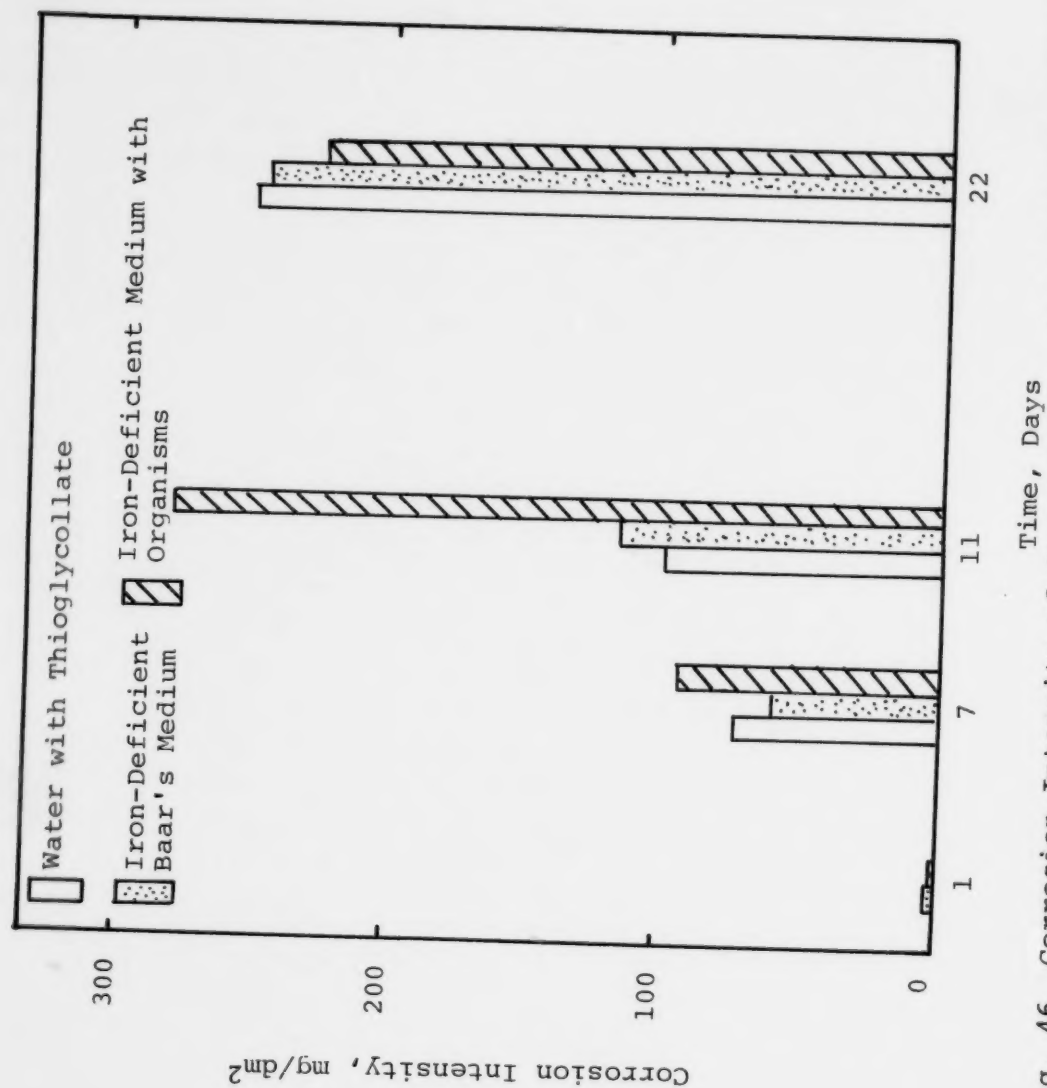
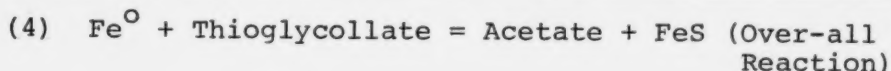
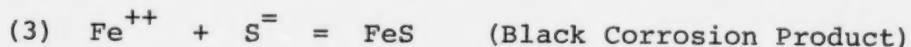
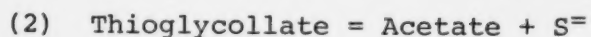


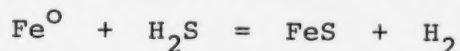
Fig. 46 Corrosion Intensity of Cast Iron Specimens Exposed to Sulfate-Reducing Organisms Grown in Iron-Deficient Baar's Medium



It is evident that thioglycollate can exert a corrosive action on iron. The oxidation-reduction potential of water decreased from -95 mv to -479 mv in 22 days. Black iron sulfide film on cast iron test specimens from the control systems (Water with thioglycollate) was evident.

The corrosion intensity of test specimens which were exposed to sulfate-reducing organisms inoculated in Baar's medium with ferrous ions increased continually with time. The analysis of total dissolved sulfide in test menstrums with organisms showed consistently high sulfide concentrations.

Horvath and Novak (108) have shown that hydrogen sulfide can give rise to serious corrosion on metals producing metal sulfides as main corrosion products. The anodic reaction is the oxidation of iron to Fe^{++} , while the simultaneous cathodic reaction is the reduction of hydrogen ion to produce hydrogen gas. The corrosion of iron by hydrogen sulfide can be expressed in the following over-all reaction:



Horvath and Novak constructed the potential/pH equilibrium diagram for the ternary system Fe-S- H_2O and interpreted the electrochemical corrosion of iron and steel in aqueous hydrogen sulfide environments (Figure 47). On the basis of the diagram, Horvath and Novak concluded that the electromotive force of the corrosion metals, such as iron, is much higher in the presence of hydrogen sulfide than for metal-water system.

The results of the present investigation support Horvath and Novak's contention that hydrogen sulfide exerts a corrosive action on iron. Results of test menstrum potentials observed in this investigation are represented in Figure 47 (Symbol x). Horvath and Novak also represented measured potentials of other investigations in the combined diagram of the systems S- H_2O and Fe-S- H_2O . It is evident that all of the observed potentials of iron and steel fall into the zone between lines (1) (2) and $\text{rH}=0$. Line (1) describes the reaction, $\text{Fe}^0 = \text{Fe}^{++} + 2e$, while the line (2) described the reaction, $\text{Fe}^{++} + \text{H}_2\text{S} = \text{FeS} + 2\text{H}^+ + 2e$.

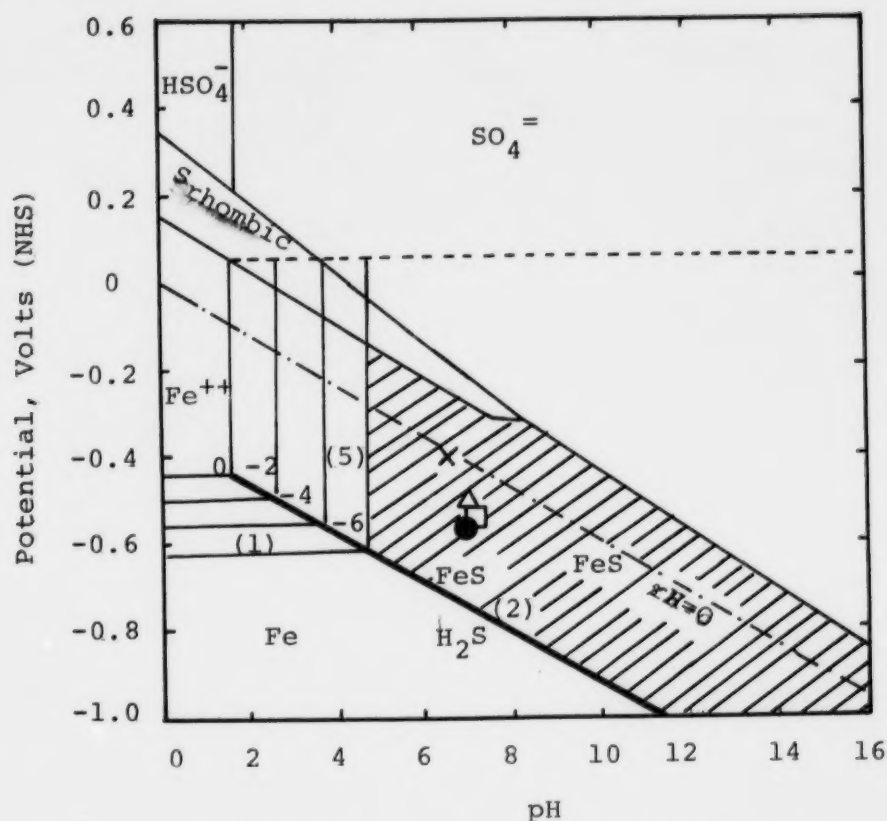


Fig. 47 Potential-pH Diagram for the Combined Systems, S-H₂O and Fe-S-H₂O.

Symbols represent the minima of potential/time curves for steel in liquid culture media inoculated with sulphate-reducing bacteria, measured by Hadley (Δ) (69), Wanklyn and Spruit ($\square$) (109), and Horvath and Novak, ($\bullet$) (108). Symbol ($\times$) represents the observed potential of cast iron test specimens exposed to Baar's Reinforced medium inoculated with sulfate-reducing organisms from UMC laboratory water.

The corrosion intensities of cast iron test specimens exposed to sulfate-reducing organisms grown in Baar's medium with and without the ferrous ions are shown in Figure 48 . Except for one case (Bottle No. 13 in the third experiment), the corrosion intensities of cast iron test specimens exposed to the experimental bottles with the sulfate-reducing organisms were higher than the comparable control bottles.

Mara and Williams (105) contended that the bacterial growth rate was an important factor in the corrosion processes of iron. Results of the present investigation concur with their observation. The bacterial growth rate as observed by the resultant by-product, hydrogen sulfide, influenced the corrosion rate of cast iron test specimens.

Mara and Williams measured the bacterial growth rate in terms of dilution rate in continuous anaerobic culture system, whereas in the present investigation growth rate was demonstrated in terms of increases in concentrations of bacteria in test menstrums. Concurrent production of hydrogen sulfide with growth of microorganisms resulted an increased rate of corrosion of iron.

King and Miller (110) have proposed an alternative mechanism for the corrosion of mild steel by the sulfate-reducing organisms. In the absence of these bacteria the activity of iron sulfide is reduced with time. They suggested the loss of activity is due to the bonding of atomic hydrogen within the iron sulfide lattice. In the presence of sulfate-reducing bacteria the activity of the iron sulfide may be restored by the disbonding of the polarizing hydrogen by the bacterial hydrogenase system. Thus, the continued high rate of corrosion observed in the natural environment might be explained in terms of the activity of iron sulfide. The production of iron sulfide is related to the growth of bacteria since, in their energy generating reaction, sulfides are produced which subsequently react with dissolved iron to produce iron sulfide.

Results of these batch culture studies elucidated that the growth of sulfate-reducing organisms influenced the corrosion rate of cast iron specimens. The average corrosion intensity of test specimens was 602 mg/dm^2 for the specimens that were exposed to organisms grown in Baar's Reinforced medium with the resultant 185 mg/l dissolved sulfide concentration after 22 days. In contrast, the average corrosion intensity was only 222 mg/dm^2 for the test specimens exposed to organisms that produced only 0.3 mg/l dissolved sulfide after 22 days.

The corrosion intensities of cast iron test specimens exposed to the experimental systems with sulfate-reducing organisms were consistently higher than the comparable control

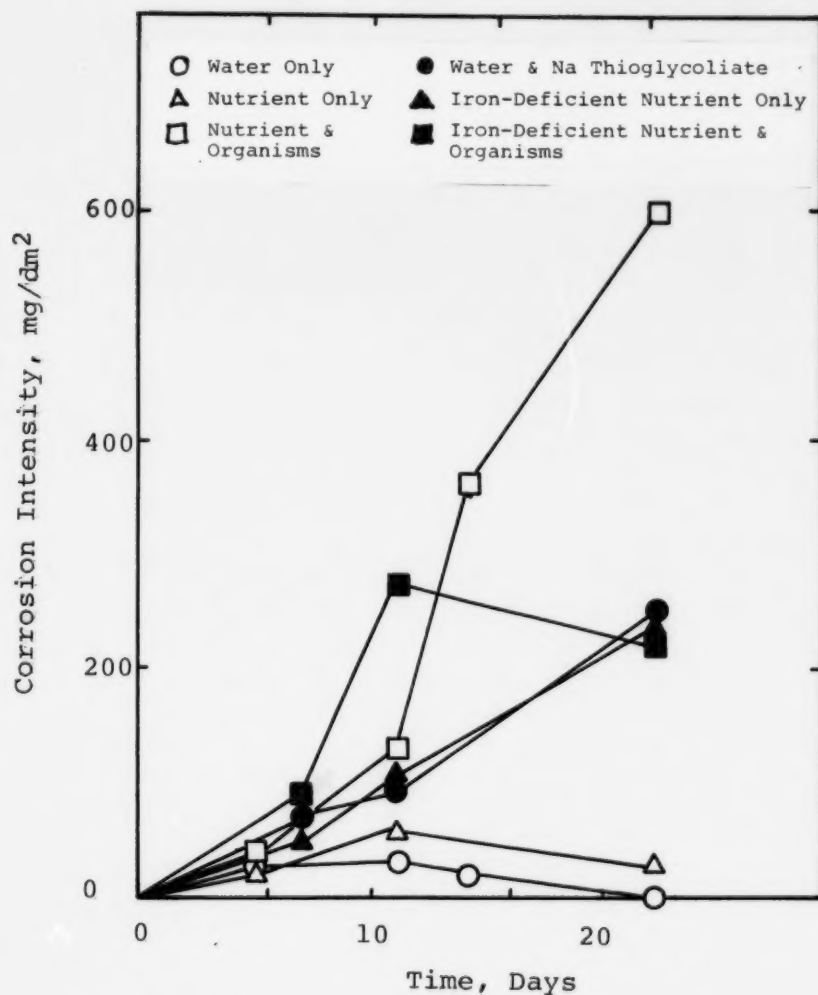


Fig. 48 Corrosion Intensities of Cast Iron Test Specimens Exposed to Water, Nutrient and Nutrient with Sulfate-Reducing Organisms

systems without organisms.

Adams and Farrer (111) and Booth, Shinn and Wakerly (112) observed the rate of corrosion to be greatly increased by the presence of added ferrous ions to the medium. Further investigations by Booth, Cooper and Wakerly (113) delineated that the effect of ferrous ions on corrosion rate to be only partially successful, i.e., only few of nine strains of sulfate-reducing bacteria increased in corrosion rate with added ferrous ions in the culture medium.

For actively growing cultures ferrous ion in medium did not influence the rate of corrosion; thus, Mara and Williams (105) concluded that ferrous ion effected corrosion rate only for the slow-growing organisms.

In the present investigation generally higher rate of corrosion was observed in the cast iron test specimens exposed to organisms growth in the Baar's medium with supplementary ferrous ions.

Effect of Aerobic Organisms on Corrosion of Cast Iron

It has been established that variations in oxygen concentration and ionic concentration at the surface of a metal will result in the corrosion of metal. Since microorganisms can grow on the surface of iron and their metabolic activities may bring about such variations, the role of microorganisms in influencing corrosion processes has been generally accepted. However, studies of aerobic microbiological corrosion of water pipes have focused mainly on iron-precipitating filamentous organisms. The role of other heterotrophic microorganisms that can proliferate in water pipes has not been evaluated with regard to the corrosion of iron in water distribution systems. In particular, the effect of aerobic heterotrophs that are found in water distribution systems has not been examined in their "natural growth condition", i.e., in drinking water.

Experiments were conducted with a number of heterotrophs that were isolated from drinking water in an effort to determine the effect of these microorganisms on the corrosion of cast iron specimens.

A. Materials and Methods

Essentially the same procedure was employed as in the previous batch studies with sulfate-reducing bacteria with following modifications: The UMC tap water was used as the test water for the experimental "growth" medium. No additional nutrient was added into the tap water. The test organisms were isolated from the pipe loop water.

After the test water was sterilized and cooled to room temperature, organisms were inoculated into a set of experimental bottles. The control bottles received no organisms. After bottles were tightly capped, they were put on the shaker to obtain a constant motion of water.

After a specified experimental period, the contents of a set of duplicate bottles were analyzed for dissolved oxygen, pH, iron, sulfate, alkalinity and bacterial plate counts. The cast iron specimens were analyzed as in the previous experiments.

B. Results and Discussions

(1) Effect of Yellow-Pigmented Heterotrophs on Corrosion of Cast Iron

One of the frequently observed yellow-pigmented polymorphic rods was studied first. This organism did not grow well on complex laboratory media such as tryptone glucose medium. The cellular morphology of yellow-pigmented heterotroph was found to be rod to amorphous shape. This aerobic heterotroph is a Gram negative, oxidase negative, MacConkey negative and catalase positive organism.

The results of the chemical analyses of the test waters are presented in Table 73. A significant decrease in dissolved oxygen was observed with the test water as a result of the sterilization process. Autoclaving with the pressurized steam resulted in the dissipation of dissolved oxygen in water. Consequently, only 1.7 mg/l of dissolved oxygen remained in the test water at the beginning of the experiment. The dissolved oxygen in the test water later had decreased to near zero. After 21 days the oxidation-reduction potential (Eh) of the test water was measured as -370 mv.

The total iron in test waters increased in both the control and experimental systems. Data indicated four to 18 fold increase in total iron concentrations in test menstrums. However, the observed iron concentration only measures the amount suspended in the test menstrum. The amount of oxidized iron attached to the test specimens was not analyzed. About 1.3 meq/l (0.39 meq alkalinity) decrease in alkalinity was observed in test systems.

In general, the density of the surviving organisms in the test water was low. The highest concentration observed was less than 0.4 percent of the original concentration. It was apparent that this organism could not proliferate in tap water under the test system conditions. The near depletion of dissolved oxygen and the minute concentrations of nutrient

Table 73 Water Analyses of Batch Study with Yellow-Pigmented Aerobic Heterotrophs

Elapsed Time Days	Experimental Conditions	D.O. mg/l	pH	Fe Diss. Total mg/l	SO ₄ ⁼ mg/l	Alkalinity meq/l	Bacterial Plate Count no./ml
0	Sterile Test System	4.9	7.8	-	36	4.3	5.0 x 10 ⁵
	Without Org.	-	7.9	1.4	36	3.0	0
	With Org.	-	7.9	1.3	36	3.0	-
	With Org.	-	8.2	2.5	43	2.8	1.5 x 10 ³
7	Without Org.	0.6	-	0.8	34	2.9	0
	With Org.	0.4	-	1.2	39	3.0	2.0 x 10 ¹
	With Org.	0.3	-	0.9	36	2.9	4.5 x 10 ²
10	Without Org.	0.8	-	-	37	3.0	0
	With Org.	0.4	-	-	37	2.9	5.9 x 10 ²
	With Org.	0.3	-	-	38	2.8	4.7 x 10 ³
15	Without Org.	0.9	-	-	34	3.2	0
	With Org.	0.3	-	-	37	2.9	4.4 x 10 ³
21	With Org.	0.1	7.5	-	29	3.3	2.0 x 10 ⁴

*Isolate No. 1: Yellow pigmented colony on tryptone glucose agar, Initial organism concentration - 5 x 10⁵ organisms per ml.

Experiment Period: September 25, 1978 - October 16, 1978

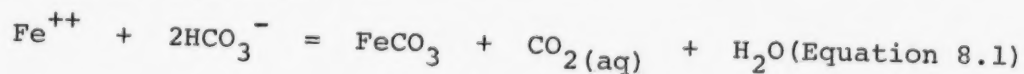
may have suppressed the growth in the test water. It is also possible that a number of organisms may have attached to the surface of the test specimens. In that case, the small number of surviving free floating organisms observed may be attributable to an incomplete sample analysis.

The total volume of a screw-cap bottle utilized in the batch study experiment is 320 ml, but the volume of water for the experiment was 305 ml. A 15 ml air space was available per test system. If one assumes the standard pressure (1 atm.) and temperature (25°C), the amount of oxygen that may be in 15 ml of air is 4.3 mg.

$$[15 \text{ ml} / 22.4 \text{ ml} \times 0.2 \times 32 \text{ mg/meq} = 4.28 \text{ mg Oxygen}]$$

The dissolved oxygen can diffuse into the test water, and subsequently may be utilized in the iron oxidation.

Generally, alkalinity in water is a reliable parameter for water analysis. When iron is oxidized, iron (Fe^{++}) may react with bicarbonate to form ferrous carbonate as shown by the following equation:



The amount of iron which would have reacted with 0.39 meq of bicarbonate is 10.9 mg. Since the average weight loss of test specimens per experimental bottle is 21.5 ± 8 mg, about 50 percent of the oxidized iron must have reacted with bicarbonate ion to form ferrous carbonate.

Analyses of test menstrum indicated increase in pH value. As it can be seen in Equation 8.1, the reaction of ferrous ion and bicarbonate ion results in the production of carbon dioxide. Carbon dioxide would dissipate in water if the concentration of carbon dioxide in water is supersaturated with respect to the dissolved carbon dioxide in air space above the liquid. Loss of carbon dioxide will result in the increase in pH of water.

The increase in pH and decrease in alkalinity of test menstrum support the reaction described in Equation 8.1.

Table 74 shows the analysis of corrosion intensity measurements of cast iron test specimens that had been exposed to yellow-pigmented organisms in tap water. The observed amount of oxidized iron, as measured by weight loss determination did not yield any noticeable difference between test specimens exposed to organisms and those in control systems. The microbiological analysis of the inoculated test menstrums

Table 74 Corrosion Intensity of Cast Iron Test Specimens
During Batch Study with Yellow-Pigmented Aerobic Heterotrophs

Elapsed Time Days	Experimental Conditions	Weight Loss mg	Exposed Area cm ²	Corrosion Intensity mg/cm ²
3	Without Org.	17.2	25.1	68.4
		14.3	25.2	56.7
	With Org.	8.4	24.5	34.3
		2.2	24.7	8.9
7	With Org.	14.3	25.0	57.1
		11.1	24.7	44.9
	Without Org.	7.2	24.3	29.6
		7.6	24.3	31.2
10	With Org.	9.8	25.1	39.0
		8.8	24.9	35.3
	With Org.	6.6	25.7	25.7
		14.4	25.2	57.0
15	Without Org.	5.7	25.5	22.3
		6.8	25.1	27.0
	With Org.	11.0	25.5	43.2
		12.0	25.2	47.6
21	With Org.	17.6	25.2	69.9
		13.6	25.2	53.9
	Without Org.	12.3	25.2	48.9
		11.5	25.5	45.0
	With Org.	5.9	24.9	23.7
		9.8	25.1	39.0
	With Org.	12.8	25.0	51.1
		17.0	25.3	67.2

Experiment Period: September 25, 1978 - October 16, 1978

showed only a low concentration of organisms. It might be that the test organisms could not acclimate to the experimental condition and remained in lag phase or moribund during the experimental period. Consequently, the microbial activity was minimal in the test systems.

The average corrosion intensity for both control and inoculated systems was 4.28 ± 15.8 mg/dm². Under the experimental conditions the corrosion intensities of test specimens exposed to organism, yellow-pigmented heterotroph, were comparable to those exposed to sterilized UMC tap water.

Although the effect of microbial growth on corrosion rate was not distinguishable, the macroscopic examination of metal surface indicated severe localized corrosion of test specimens. It is evident that the effect of microorganisms on corrosion of iron specimens is enhancing localized corrosion on metal.

A second batch culture experiment was conducted with the same yellow-pigmented organism. The experimental procedure was same as in the previous experiment. However, in this experiment only 250 ml of test water was added into each reaction bottle in order to leave more air space for more oxygen diffusion. About 18 mg of oxygen would be available in 63 ml of air space, assuming 1 atm and 25°C.

The results of test water analyses are shown in Table 75. The water quality change was similar to that observed in the previous experiment. A depletion of dissolved oxygen and increase in total iron concentration were evident in both the sterile and inoculated systems. The initial concentration of organism in inoculated bottles was 4.9×10^4 per ml. After 6 days the surviving organisms varied from 1 to 50 percent of the original concentration. Test periods of 15 days resulted in further reductions to 1 to 10 percent of the original concentration. Again, the adverse conditions including low concentration of available nutrient may have resulted in low numbers of surviving organisms.

The corresponding corrosion intensities of the cast iron test specimens exposed to test menstrum, with and without the yellow-pigmented organism, are presented in Table 76. The average corrosion intensity of test specimens which were exposed to systems with organisms was higher by 44 percent and 32 percent respectively, for samples observed 6 and 15 days of experiment (Figure 49). Some enhancement of corrosion was observed in the systems with organisms. Again, it was clearly evident that the effect of microorganisms on corrosion of cast iron to be promoting localized corrosion on metal surface. The surface of test specimens exposed to test menstrums with

Table 75 Water Analyses of Batch Study with Yellow-Pigmented Aerobic Heterotrophs

Elapsed Time Days	Experimental Conditions	D.O. mg/l	Eh mv	pH	Fe mg/l	Alkalinity meq/l	SO ₄ ⁼ mg/l	Bacterial Plate Count no./ml
0	Sterile Test System	6.3	NM	7.9	0.4	4.5	NM	-
1	Without Org.	2.8	NM	7.7	4.1	4.0	NM	-
6	With Org.	0.6	-150	7.8	26.0	3.5	NM	5.1 x 10 ²
	With Org.	0.4	-230	7.8	37.5	3.8	NM	2.4 x 10 ⁴
	Without Org.	0.4	-250	7.9	40.0	3.6	NM	0
15	With Org.	0.8	NM	7.8	34.0	4.1	35	5.1 x 10 ²
	With Org.	0.6	NM	7.8	46.0	3.4	34	4.6 x 10 ³
	Without Org.	0.9	NM	7.7	57.5	4.3	36	0

Initial organism concentration: 5×10^4 /ml

Experimental Period: October 26 - November 10, 1978

Table 76 Corrosion Intensity of Cast Iron Test Specimens during Batch Study with Yellow-Pigmented Aerobic Heterotrophs

Elapsed Time Days	Experimental Conditions	Cast Iron Test Specimens Weight Less mg	Corrosion Intensity mg/dm ²
1	Without Org.	6.5	26
		6.7	27
6	With Org.	27.6	111
		28.4	114
	With Org.	30.2	121
		29.7	119
15	Without Org.	16.1	65
		16.2	65
	With Org.	30.1	121
		33.4	134
	With Org.	31.7	127
		31.2	125
	Without Org.	21.8	88
		21.1	85

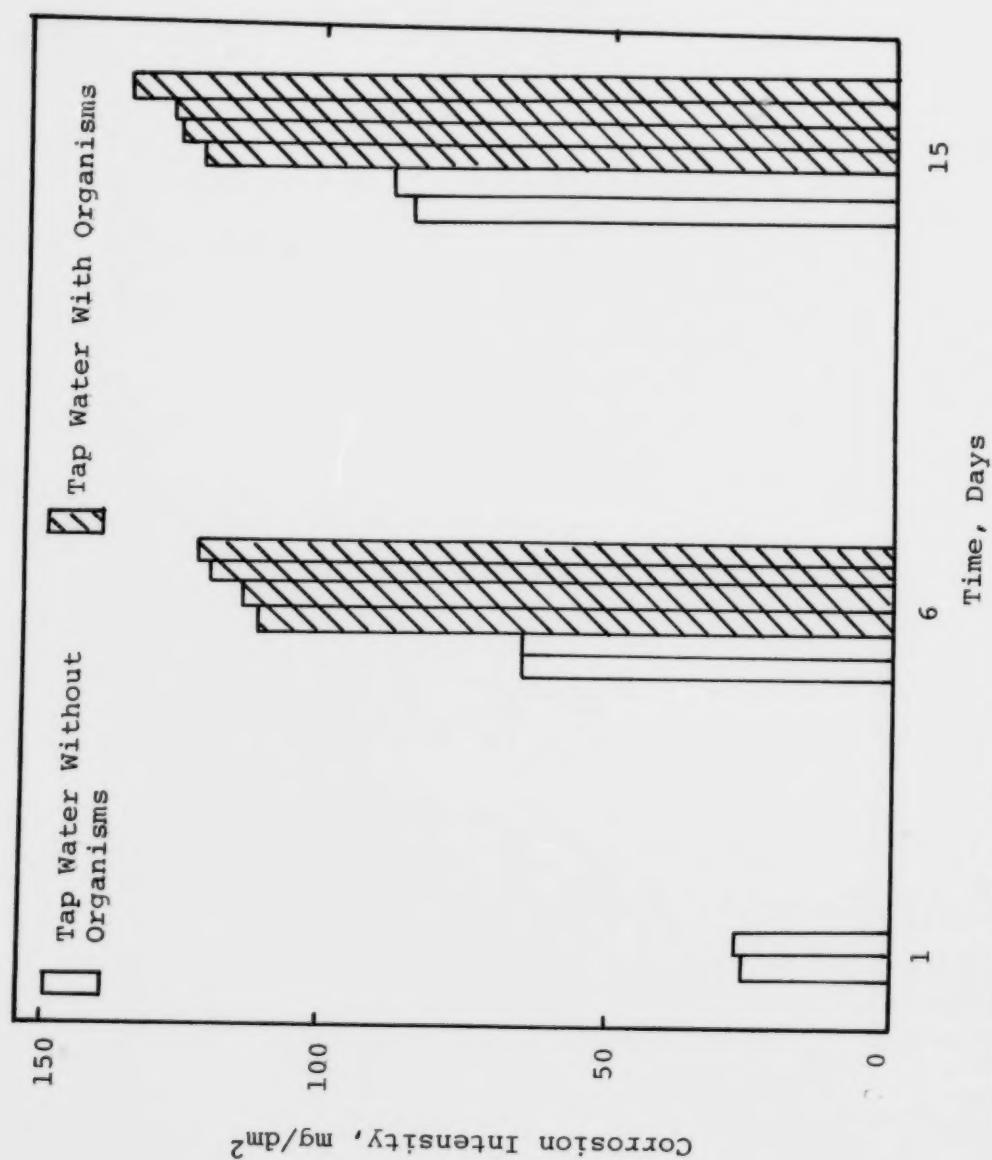


Fig. 49 Corrosion Intensity of Cast Iron Specimens Exposed to Yellow-Pigmented Aerobic Heterotrophs Grown in UMC Tap Water

organisms exhibited pitted corrosion, whereas, the surface of test specimens exposed to test menstrums without the organisms showed more uniform corrosion of metal.

During this experiment alkalinity of test water decreased about 0.2 meq. Analysis of alkalinity indicated that about 23 to 32 percent of oxidized iron could be attributed to the formation of ferrous carbonate in sterilized tap water system. Only about 5 to 15 percent of the oxidized iron could be attributed to decrease in alkalinity in test systems with organisms. This difference in corrosion processes with and without the organism may imply that direct chemical oxidation of iron does not dominate the overall corrosion of iron.

Microorganisms may grow on the surface of iron and form minute colonies. Chemical precipitates such as iron oxide and carbonate may form larger accumulations with microorganisms. Consequently, a number of localized tubercles may be established on test specimens. There would be a differential oxygen and ionic concentration cell on the metal surface with a potential difference between the area inside the tubercle and the outside the tubercle. The corrosion reaction cell would cause localized corrosion of metal. Results of the present investigation give credence to the concept of concentration cell for biologically mediated corrosion.

(2) Effect of Non-Pigmented Aerobic Organisms on Corrosion Rate

Another frequently observed non-pigmented Gram negative rod was examined to evaluate the effect of this organism on the corrosion rate of cast iron test specimens. This organism was oxidase positive, catalase positive, MacConkey negative and able to precipitate ferric oxide when grown in ferric ammonium citrate mineral medium.

The same experimental method was employed as in the previous experiments. The initial organism concentration was 1.6×10^4 per ml. As in the other experiments, some corrosion of test specimens occurred as a result of the sterilization process. Approximately 3 mg/l of iron was observed in freshly sterilized bottles.

Table 77 presents the results of the water analysis. The corrosion intensity of cast iron test specimens, in the presence and absence of the test organisms, is presented in Table 78. Again, in this study a near depletion of dissolved oxygen was observed. Average of 0.5 meq/l (0.15 meq alkalinity) decrease in alkalinity was observed in test menstrum of this organism. The iron concentration in the test menstrum increased 10 to 20 fold due to the corrosion of the test

Table 77 Water Analyses of Batch Study with Non-Pigmented Aerobic Heterotrophic Rods

Elapsed Time Days	Experimental Conditions	D.O. mg/l	pH	Fe Diss. Total mg/l	SO ₄ ⁼ mg/l	Alkalinity meq/l	Bacterial Plate Count no./ml
0	Initial Test Water	2.1	7.9	-	36	5.0	1.6×10^4
3	With Org.	0.5	NM	0.7	57	4.6	4.0×10^4
	With Org.	0.7	NM	0.3	62	4.5	7.1×10^4
8	Without Org.	0.5	NM	-	28	4.6	$1.5 \times 10^{2*}$
	With Org.	0.4	NM	-	34	4.5	1.6×10^3
10	With Org.	0.3	NM	-	41	4.5	1.5×10^3
	With Org.	0.5	7.9	-	59	4.4	1.2×10^5
15	With Org.	0.7	7.9	-	34	4.4	4.2×10^4
	Without Org.	1.2	7.6	-	41	4.4	0
	With Org.	0.2	7.7	-	56	4.6	7.9×10^3
	With Org.	0.3	7.5	-	38	4.5	2.5×10^3

* Contaminant organisms observed in sterilized water
Experimental Period: October 2 - 17, 1978

Table 78 Corrosion Intensity of Cast Iron Test Specimens during Batch Study with Non-Pigmented Aerobic Heterotrophs

Elapsed Time Days	Experimental Conditions	Weight Loss	Exposed Area cm^2	Corrosion Intensity mg/dm^2
Initial Water 3	With Org.	8.5	24.8	34.3
	With Org.	8.4	25.2	33.5
	With Org.	9.7	24.8	39.1
8	Without Org.	9.9	24.7	40.1
	Without Org.	12.6	24.7	51.0
	Without Org.	11.1	25.3	43.9
10	With Org.	18.0	24.6	73.2
	With Org.	10.5	25.2	41.7
	With Org.	13.2	24.4	54.1
15	Without Org.	13.5	24.9	54.2
	Without Org.	18.1	24.4	74.2
	Without Org.	19.8	24.4	81.1
	With Org.	13.9	24.4	57.0
	With Org.	16.6	24.4	68.0
	With Org.	15.8	25.1	62.9
	Without Org.	16.2	24.3	66.7
	Without Org.	9.0	25.2	35.7
	Without Org.	20.0	25.2	79.4
	With Org.	15.1	24.6	61.4
	With Org.	12.0	25.0	48.0

specimens.

The average test specimen weight loss was 13.6 ± 3.7 mg. For each experimental system there were two test specimens. Therefore, the average total weight loss of iron was 27.2 ± 7.4 mg. The average weight loss of test specimens in the previously studied yellow-pigmented organism was 21.5 ± 8 mg. Two values are comparable even though two organisms are different.

Microbiological analysis of the test water did not yield consistent result. At times, the bacterial density had increased seven-fold (after 10 days), while at other times, (after 8 days and 15 days), only 10 to 50 percent of the original bacterial concentration was observed. Bacterial analysis indicated that the control bottle, which had not been inoculated with test organisms, showed low concentrations of contaminant organisms.

After 24 hours, the test specimens in the reaction bottle inoculated with organisms exhibited a thick layer of ferric oxide precipitates. Tuberculation increased with longer exposure time. When the tubercles were removed, severe localized pit corrosion was observed on the test specimens. In contrast, where no organism was present in the test menstrum, the test specimens exhibited a more uniform textured corrosion of metal surface.

Since this organism can precipitate ferric oxide, tubercle formation from the cast iron test specimens by this organism could have initiated a differential concentration cell and established an oxygen gradient over limited surface of the test specimen. A differential potential between the site below the tubercle and the site outside of adjacent to the tubercle could have resulted in corrosion reactions. Thus, microorganisms might be amenable to the localized corrosion of cast iron specimens. This observation might be supportive to the hypothesis of differential concentration cell by Olsen and Szybalski (38).

(3) Effect of Non-Pigmented Vibrio-Shaped Organism on the Corrosion of Cast Iron Test Specimens

This vibrio-shaped organism was also frequently observed in water from the pipe loop studies. The colonies observed on the plate count medium were generally non-pigmented initially. However, older cultures showed pink color at times. It was tentatively identified as specie belonging to Caulobacter group.

A cell suspension was made in sterile buffered water. The same experimental procedure was followed as in the previous

batch culture studies with one exception. Only 250 ml of test menstrum was added into each experimental bottle. The initial concentration of test organism was 1.68×10^5 per ml.

The results of the experiment with the vibrio-shaped organism in the batch culture studies are presented in Table 79 and 80 . In this study, the vibrio organism did not die in the limited oxygen environment. Instead, they maintained viability during the two week experimental period. A nearly 50 fold increase in organism concentration was observed after 15 days of exposure. The most significant water quality change in the test menstrum was again the increase in the total iron concentration. A more than 20 fold increase in total iron concentration was observed in test water. A near depletion of dissolved oxygen concentration was observed in the test menstrums from systems analyzed after 4 and 11 days. In other test systems, systems analyzed after 8 and 15 days, observed changes were not significant. Changes in other water quality parameters, sulfate and pH, were minimal. Again, decrease in alkalinity was noted, and attribute the change to a reaction between ferrous ion and bicarbonate ion. During this experiment 0.63 meq decrease in alkalinity was observed. This would correspond to 17.6 mg of ferrous ion to have reacted with bicarbonate ion to form ferrous carbonate.

The corrosion intensities of test specimens exposed to vibrio-shaped organisms are shown in Figure 50 . With this experiment generally higher rate of corrosion intensity was noted than what has been observed in the previous experiments with heterotrophs. Perhaps more air space available above the test menstrum may have attributed this difference.

It was evident that the systems with higher corrosion rate were usually those with higher dissolved oxygen concentrations. The average corrosion intensities of test specimens in experimental bottles with organisms were 232.7 mg/dm^2 , 80 mg/dm^2 and 189 mg/dm^2 for test specimens analyzed after 8 days, 11 days and 15 days, respectively.

An appreciable difference in corrosion intensity of test specimens was noted with samples that were exposed to vibrio-shaped organisms for 15 days. Compared to the control systems test specimens exposed to vibrio-shaped organisms showed three to six fold increases in corrosion rate. The difference in corrosion rates observed after the shorter experimental period was not as much as the difference noted after the prolonged exposure time. This might be an important observation. Since the effect of microbial growth on corrosion of iron was to enhance the localized "pit" corrosion, the net corrosion rate with organism may not be noticeably high initially, if the corrosion rate was measured by test specimen weight loss

Table 79 Water Analyses of Batch Study with *Vibrio* Organisms

Elapsed Time Days	Experimental Conditions	D.O. mg/l	Eh mv	Fe mg/l	pH	Alkalinity meq/l	SO ₄ ⁼ mg/l	Plate Count no./ml
0	Sterile Test System	2.8	NM	2.9	7.9	4.1	NM	1.7 x 10 ⁵
4	With Org.	0.5	+ 80	20	7.9	3.3	NM	4.0 x 10 ⁵
	With Org.	0.9	+170	30	7.8	3.3	NM	5.0 x 10 ⁵
8	Without Org.	2.6	NM	33	7.9	3.0	34	0
	With Org.	2.1	NM	66	8.0	2.8	34	1.7 x 10 ⁶
	With Org.	3.2	NM	43	8.3	2.7	32	5.1 x 10 ⁶
11	With Org.	0.3	- 60	68	7.8	3.6	35	6.0 x 10 ⁶
	With Org.	0.3	-170	46	7.8	3.4	34	1.1 x 10 ⁶
15	Without Org.	1.0	NM	83	7.6	3.5	36	0
	With Org.	1.3	NM	41	7.7	3.6	38	8.5 x 10 ⁶
	With Org.	1.6	NM	69	7.8	3.4	34	6.7 x 10 ⁶

Experimental Period: October 12 - 27, 1978

Table 80 Corrosion Intensity of Cast Iron Test Specimens
during Batch Study with *Vibrio* Organisms

Delayed Time Days	Experimental Conditions	Weight Loss mg	Exposed Area cm ²	Corrosion Intensity mg/dm ²
4	With Org.	12.6	25.0	50.4
		9.7	24.7	39.3
		11.5	25.0	46.0
8	With Org.	10.0	25.0	40.0
		49.2	25.2	195.2
	Without Org.	51.8	25.0	207.2
		67.2	24.9	269.9
		64.5	25.2	256.0
11	With Org.	52.5	25.0	210.0
		48.7	25.0	194.8
	Without Org.	24.9	24.8	100.4
		25.5	25.3	100.8
		14.5	24.8	58.5
15	With Org.	15.1	25.3	59.7
		9.9	24.7	40.1
	Without Org.	12.6	25.3	49.8
		72.6	25.0	290.4
		53.5	24.9	214.9
	With Org.	30.1	24.7	121.9
		32.2	25.0	128.8

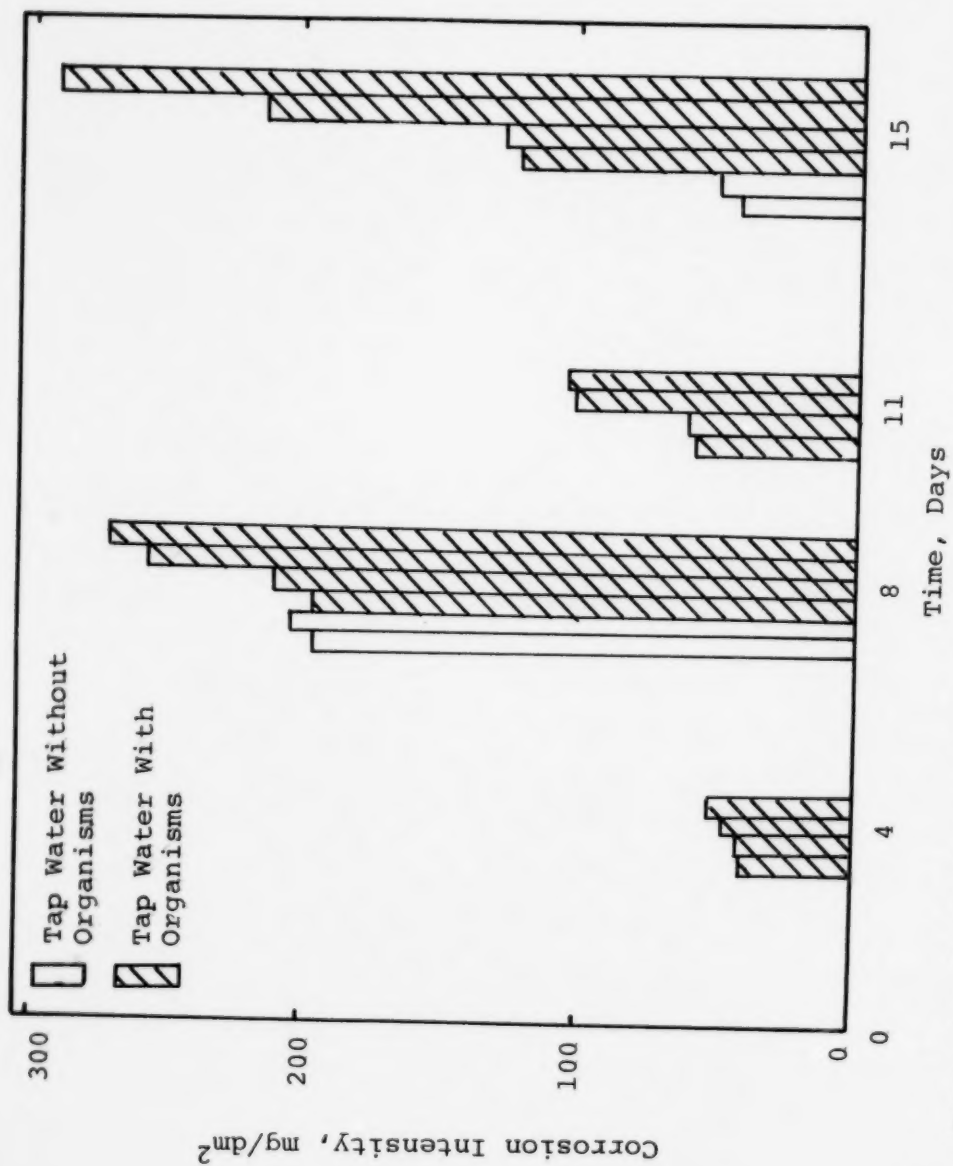


Fig. 50 Corrosion Intensity of Cast Iron Test Specimens Exposed to *Vibrio* Organisms Grown in UMC Tap Water

determination with time. However, on prolonged exposure of test specimens to corrosive test menstrums the localized corrosion can yield measureable weight loss with time. Under this precept it would seem logical that the net difference in corrosion rates with and without the test organism would be observed in test systems analyzed after 15 days but not necessarily after 8 days.

From these individual batch culture corrosion studies the following observations were noted:

- (1) The corrosion of cast iron specimens was essentially controlled by the available dissolved oxygen. Iron oxidation as measured by the weight loss of cast iron specimens was generally higher in systems that had more air space above the test menstrum. Test specimens exposed to yellow-pigmented organism showed 43 mg/dm^2 corrosion intensity when the available air space was 15 ml. However, test specimens exposed to the same yellow-pigmented organism showed up to 127 mg/dm^2 corrosion intensity when the available air space was increased to 63 ml.
- (2) The corrosion of test specimens was localized corrosion of metal when microorganisms were inoculated in the test system. All three microorganisms exhibited influence of inducing localized corrosion on initially smooth surface cast iron test specimens. Perhaps, for this difference in corrosion process, the effect of microorganism on corrosion rate of test specimens was not observed until prolonged exposure time.
- (3) When corrosion intensities of three aerobic heterotrophs were compared, the vibrio-shaped organism showed a slightly higher rate of corrosion intensities, as seen by Figure 51 .
- (4) Test specimens exposed to vibrio-shaped organism showed three to six fold higher corrosion rate than the comparable control systems after 15 days of experiment.
- (5) Decrease in alkalinity was observed in all test systems. This change in alkalinity was attributed to the reaction between oxidized iron and bicarbonate to form ferrous carbonate in oxygen limited environment. The change in pH of test menstrum supported this reaction concept.

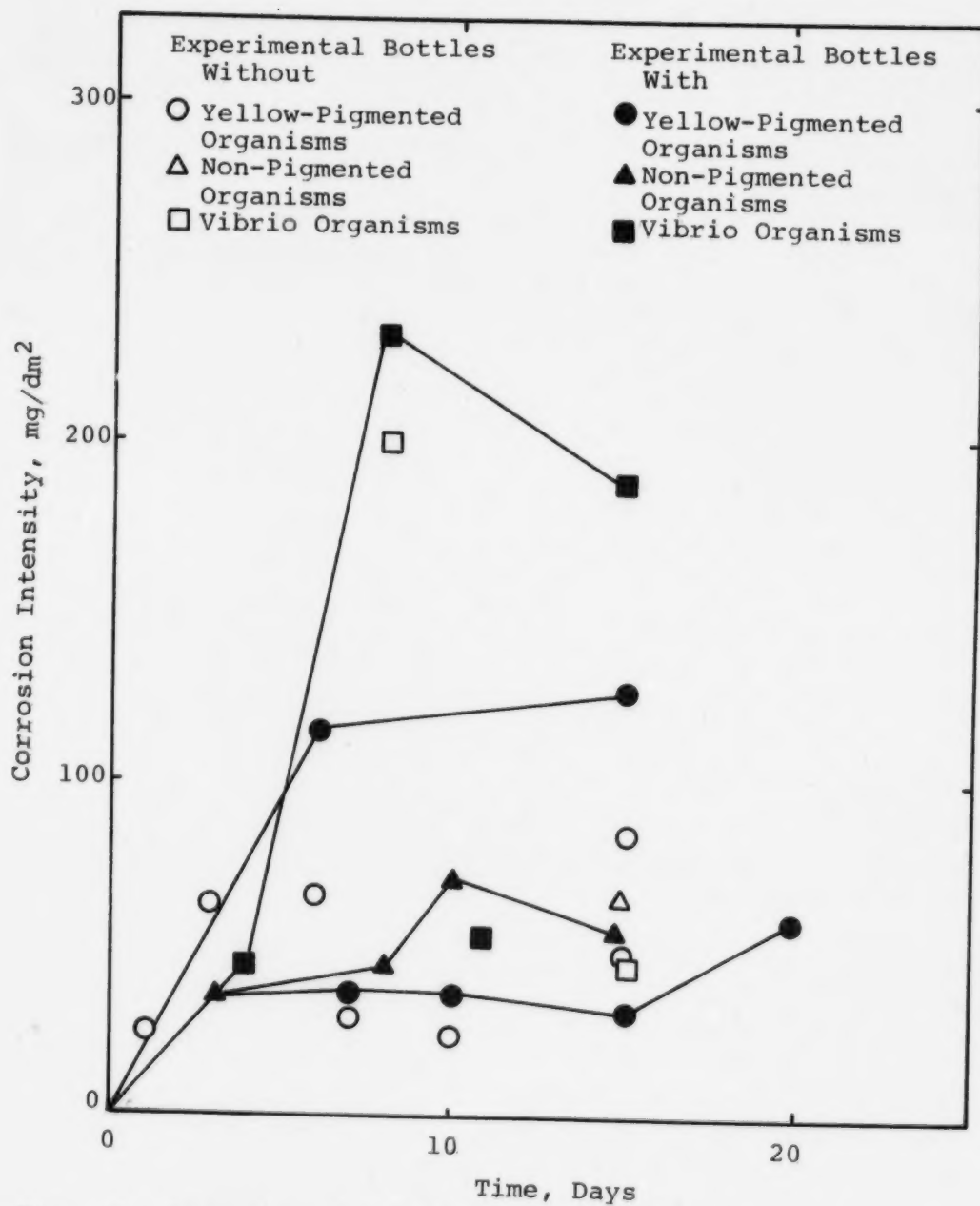


Fig. 51 Corrosion Intensities of Cast Iron Test Specimens Exposed to Three Aerobic Heterotrophs from Pipe Loop Water

Effect of Mixed Cultures of Microorganisms on the Corrosion Rate of Cast Iron Specimens

A batch corrosion study was conducted with loop water to evaluate the effect of a mixed population of microorganisms on the corrosion of cast iron test specimens. The second experiment was performed with loop water which had been supplemented with pipe deposits from the steel pipe loop systems. Because of the incongruity in equating microbial growth and corrosion intensity of test specimens, the latter experiment attempted to include all the necessary elements of the distribution pipe environment, i.e., microorganisms, pipe deposits and the indigenous chemical constituents of drinking water.

A. Materials and Methods

Pipe loop water was collected from the steel pipe loop system No. 3 and refrigerated at 4°C. A portion of loop water was sterilized while the remainder was left unsterilized. Each experimental bottle contained 250 ml of loop water. Therefore, 18 mg of oxygen would be available at 25°C.

Cast iron test specimens were prepared as in the previous experiments, i.e., degreased, washed and preweighed. Weight loss was determined after the removal of corrosion products.

After the initial water quality of the test menstrum was determined, the experimental bottles were put on a shaker to provide mixing.

Microbiological analysis was limited to bacterial enumeration in tryptone glucose medium for aerobic/facultative anaerobic organisms. Chemical analysis was conducted for dissolved oxygen, total iron, pH, alkalinity and sulfate ion concentrations.

B. Results and Discussions

Results of test menstrum analyses are presented in Table 81 for the first experiment. Similarly, water quality analysis for the second experiment with mixed cultures is presented in Table 82.

The dissolved oxygen concentrations varied from 1.2 to 8.5 mg/l for the first experiment, while those in the second experiment ranged between 0.8 to 9.2 mg/l.

About 0.15 to 0.39 meq decrease in alkalinity was observed in test menstrums from the first experiment, while 0.12 to 0.75 meq decrease in alkalinity was observed in test menstrums from the second experiment. The highest decrease in alkalinity (0.75 meq) was noted in the sterilized loop water with pipe deposits after 26 days of experimental period.

Table 81 Loop Water Analyses of Batch Study with the Acclimated Microbial Populations in Loop Water

Elapsed Time Days	Experimental Conditions	D.O. mg/l	pH	Fe mg/l	Alkalinity meq/l	SO ₄ ⁼ mg/l	Bacterial Plate Count no./ml
0	Initial Water	6.4	8.0	0.1	3.4	30	3.0 x 10 ⁴
4	Without Org.	1.9	7.7	6	2.9	NM	0
	With Org.	7.6	7.8	6	2.2	NM	1.9 x 10 ⁵
	With Org.	7.7	7.8	12	2.3	NM	1.2 x 10 ⁵
9	Without Org.*	7.3	8.3	68	2.2	NM	2.5 x 10 ¹
	With Org.	6.2	7.5	70	2.4	NM	1.5 x 10 ⁵
	With Org.	8.5	8.1	66	2.2	NM	1.2 x 10 ⁵
14	Without Org.*	7.2	8.8	63	2.1	34	2.4 x 10 ³
	With Org.	1.2	7.6	140	4.2	33	3.7 x 10 ⁵
	With Org.	4.7	7.5	52	2.8	33	2.8 x 10 ⁵
19	Without Org.*	6.4	8.4	37	2.1	35	1.9 x 10 ¹
	With Org.	7.4	8.2	81	2.1	31	1.3 x 10 ⁴
	With Org.	1.8	7.7	35	2.6	38	3.0 x 10 ³

*Contaminant organisms observed in sterilized loop water
Experimental Period: November 27 - December 16, 1978

Table 82 Analyses of Loop Water (with Supplementary Sediments) during Batch Study with the Acclimated Microbial Populations in Loop Water

Elapsed Time Days	Experimental Conditions	D.O. mg/l	pH	Fe mg/l	Alkalinity meq/l	SO ₄ mg/l	Bacterial Plate Count no./ml
0	Without Org.	NM	7.8	16	4.2	29.5	2.0×10^5
5	With Org.	8.4	8.2	88	3.0	35.0	9.5×10^4
	With Org.	0.9	7.5	35	4.0	35.0	7.4×10^4
	With Org.	3.9	7.8	72	3.0	25.5	1.2×10^5
	With Org.	7.3	8.2	60	3.1	25.5	1.4×10^5
	Without Org.	0.9	8.2	20	3.8	27.5	0
	Without Org.	8.0	9.7	56	3.4	24.0	0
12	With Org.	7.0	8.2	35	2.6	37.0	3.7×10^5
	With Org.	8.7	8.7	59	2.6	36.0	1.7×10^5
	With Org.	9.0	8.0	53	2.6	38.0	2.0×10^5
	With Org.	9.2	8.2	53	2.7	25.0	3.1×10^5
	Without Org.	1.1	8.4	37	3.5	NM	$3.3 \times 10^{5*}$
	Without Org.	8.9	9.2	21	2.7	23.5	0

Table 82 Analyses of Loop Water (with Supplementary Sediments) during Batch Study with the Acclimated Microbial Populations in Loop Water (continued)

Elapsed Time Days	Experimental Conditions	D.O. mg/l	pH	Fe mg/l	Alkalinity meq/l	SO ₄ ⁼ mg/l	Bacterial Plate Count no./ml
18	With Org.	0.8	7.3	62	3.8	47.5	1.1 x 10 ⁵
	With Org.	8.3	8.2	204	2.4	39.0	4.3 x 10 ⁴
	With Org.	8.4	8.3	63	2.4	39.0	2.6 x 10 ⁵
	With Org.	8.4	8.5	82	2.4	33.5	2.0 x 10 ⁵
	Without Org.	7.6	9.1	61	2.6	27.0	1.0 x 10 ^{3*}
	Without Org.	8.5	9.2	75	2.8	27.0	1.0 x 10 ^{3*}
26	With Org.	8.2	8.3	44	2.3	NM	1.3 x 10 ⁵
	With Org.	8.0	8.6	42	2.2	NM	8.4 x 10 ⁴
	With Org.	7.1	8.8	23	2.3	NM	9.6 x 10 ⁴
	With Org.	7.6	9.0	40	2.6	NM	5.5 x 10 ⁴
	Without Org.	4.5	9.5	15	1.6	NM	0
	Without Org.	1.8	9.7	35	1.7	NM	0

* Contaminant Organisms observed in Sterilized Loop Water with Sediments
Experiment Period: December 22, 1978 - January 17, 1979

The iron concentration in the experimental water increased 60 to 1400 fold due to the corrosion of the test specimens. With mixed culture studies definitely higher amount of corrosion was observed.

The concentration of microorganisms, as determined by the plate count method on tryptone glucose medium at room temperature, increased up to 14 days. Thereafter, the density of organisms decreased to 10 percent of the original concentration. In the presence of pipe sediments a better survival of microorganisms was observed in all experimental systems. Unfortunately, several presterilized test menstrums showed bacterial contamination.

An important observation is that the organisms from the pipe loop system water can maintain viability as a mixed culture, whereas, individually, these organisms cannot maintain their viability as well.

The sulfate ion measurements in the second experiment were not accurate because sediments in the test menstrum interfered with their analyses.

Since the resultant dissolved oxygen concentrations were inconsistent, the experimental systems were categorized according to the observed dissolved oxygen concentration/range (Table 83). The majority of experimental systems belonged to the group exhibiting high dissolved oxygen (7.0 - 9.2 mg/l). Another group of experimental systems showed low dissolved oxygen (less than 2 mg/l). There were some systems with intermediate dissolved oxygen concentrations (3.5 - 6.4 mg/l).

Corrosion intensities of cast iron test specimens exposed to pipe loop water are presented in Table 84 . Similarly, corrosion intensities of cast iron test specimens exposed to pipe loop water with sediments are presented in Table 85 . Generally, corrosion intensities of cast iron test specimens increased with time (Figure 52).

When the dissolved oxygen was above 7 mg/l in the test systems, the average corrosion intensity of cast iron specimens exposed to unsterilized loop water was 552.5 mg/dm² for specimens exposed for 5 days, 1038 mg/dm² for specimens exposed for 12 days, 1569.6 mg/dm² for specimens exposed for 18 days and 1981.2 mg/dm² for specimens exposed for 26 days.

The average corrosion intensity of cast iron specimens exposed to the sterilized loop water was 610 mg/dm² for specimens exposed for 5 days, 880 mg/dm² for specimens exposed for 12 days and 1152 mg/dm² for specimens exposed for 18 days.

Table 83 Corrosion Intensities of Cast Iron
Specimens Exposed to Loop Water

Exposed Time Days	Average Corrosion Intensity of Test Specimens Exposed to	
	<u>Sterilized Loop Water</u> mg/dm ²	<u>Unsterilized Loop Water</u> mg/dm ²
<u>Low Dissolved Oxygen (Less than 2 mg/l)</u>		
4	232	NM
5	180	164
12*	271	NM
14	NM	286
18	NM	193
19	NM	1115
26	NM	1429
<u>Dissolved Oxygen between 3.5-6.4 mg/l</u>		
5	NM	389
9	NM	652
14	NM	629
19*	1324	NM
26	1486	NM
<u>High Dissolved Oxygen (Greater than 7 mg/l)</u>		
4	NM	421, 476
5	610	520, 586
9	814	790
12	880	890, 967, 1088, 1202
14	NM	1192
18	1127, 1170	1580, 1587, 1609
19	NM	1600
26	NM	1815, 1880, 2051, 2178

* Contaminant organisms observed in sterilized loop water

NM: Not Measured

Table 84 Corrosion Intensity of Cast Iron Test Specimens during Batch Study with the Acclimated Microbial Populations in Loop Water

Elapsed Time Days	Experimental Conditions	Weight Loss mg	Exposed Area cm^2	Corrosion Intensity mg/dm^2
4	Without Org.	31.2	13.4	232.8
	With Org.	30.9	13.4	230.6
	With Org.	64.3	13.4	479.8
9	With Org.	62.9	13.3	472.9
	Without Org.*	54.9	13.1	419.1
	Without Org.*	57.2	13.5	423.7
	With Org.	110.5	13.5	818.5
	With Org.	109.3	13.5	809.6
	With Org.	89.2	13.5	660.7
14	With Org.	85.6	13.3	643.6
	Without Org.*	110.8	13.3	833.1
	With Org.	100.2	13.4	747.8
	With Org.	166.2	13.4	1240.3
	With Org.	155.5	13.6	1143.4
	With Org.	37.5	13.3	282.0
19	With Org.	39.1	13.5	290.0
	Without Org.*	84.2	13.5	623.7
	Without Org.*	84.3	13.3	633.8
	Without Org.*	187.6	13.4	1400.0
	With Org.	167.3	13.4	1248.5
	With Org.	216.1	13.5	1600.0
	With Org.	214.4	13.4	1600.0
	With Org.	145.6	13.4	1086.6
		153.1	13.4	1142.5

* Contaminant Organisms observed in Sterilized Loop Water
Experimental Period: November 27, 1978 - December 16, 1978

Table 85 Corrosion Intensity of Cast Iron Test Specimens during
Batch Study with the Acclimated Microbial Populations in Loop Water
(with Supplementary Sediments)

Elapsed Time Days	Experimental Conditions	Weight Loss mg	Exposed Area cm ²	Corrosion Intensity mg/dm ²
5	With Org.	76.5	13.6	562.5
		82.3	13.5	609.6
	With Org.	21.3	13.4	159.0
		22.6	13.4	168.7
	With Org.	51.1	13.5	378.5
		53.5	13.4	399.2
	With Org.	68.1	13.5	504.4
		71.2	13.3	535.3
	Without Org.	26.0	13.3	195.5
		22.0	13.4	164.2
	Without Org.	78.8	13.4	588.1
		84.7	13.4	632.1
12	With Org.	119.5	13.4	891.8
		120.0	13.5	888.9
	With Org.	160.4	13.5	1188.1
		164.1	13.5	1215.6
	With Org.	125.1	13.3	940.6
		131.2	13.2	993.9
	With Org.	142.2	13.4	1061.2
		148.3	13.3	1115.0
	Without Org. *	36.2	13.3	272.2
		36.0	13.3	270.7
	Without Org.	114.9	13.4	857.5
		121.0	13.4	903.0

Table 85 Corrosion Intensity of Cast Iron Test Specimens during Batch Study with the Acclimated Microbial Populations in Loop Water (with Supplementary Sediments) (continued)

Elapsed Time Days	Experimental Conditions	Weight Loss mg	Exposed Area cm ²	Corrosion Intensity mg/dm ²
18	With Org.	26.9	13.6	197.8
		25.1	13.4	187.3
		205.9	13.5	1525.2
	With Org.	215.7	13.2	1634.1
		218.4	13.6	1605.9
	With Org.	219.2	13.6	1611.8
		207.7	13.4	1550.0
		212.8	13.1	1624.4
	Without Org.*	151.0	13.3	1135.3
	Without Org.*	150.0	13.4	1119.4
		158.9	13.4	1185.8
		155.9	13.5	1154.8
26	With Org.	271.2	13.4	2023.9
	With Org.	280.5	13.5	2077.8
		274.9	13.2	2082.6
	with Org.	304.5	13.4	2272.4
		247.2	13.3	1858.6
	With Org.	251.0	13.2	1901.5
		236.0	13.2	1787.7
	With Org.	248.8	13.5	1843.0
		200.8	13.8	1455.1
	Without Org.	207.7	13.6	1527.2
		407.0	29.8	1365.8
		377.6	25.3	1492.5

*Contaminant organisms observed in sterilized loop water

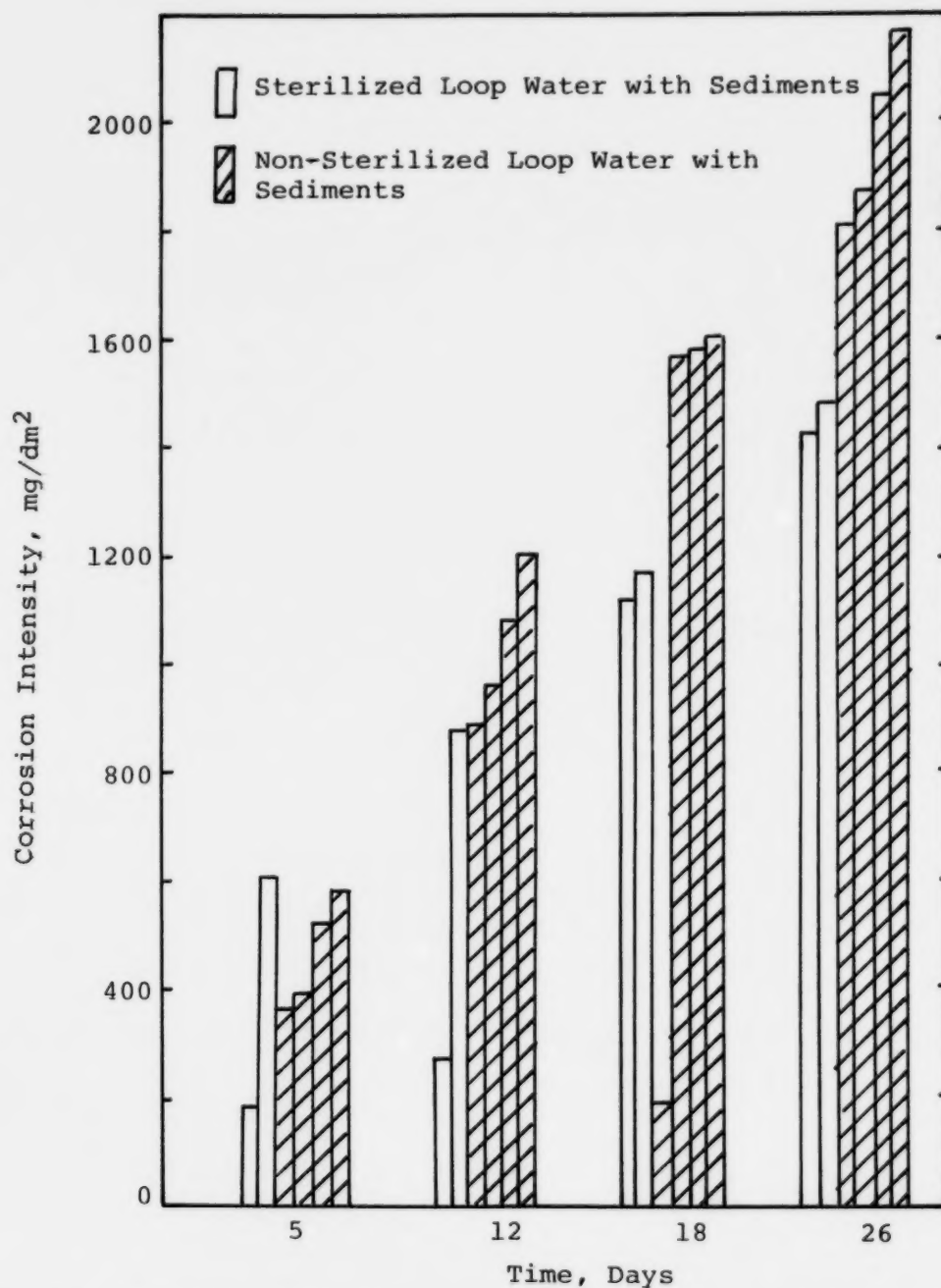


Fig. 52 Corrosion Intensity of Cast Iron Test Specimens in Batch Reactors with the Acclimated Microbial Populations and Supplementary Sediments

When the corrosion intensities of cast iron test specimens were expressed in terms of the observed dissolved oxygen concentration ranges, the effect of dissolved oxygen seemed to be more important controlling parameter than the effect of the microbial growth. Therefore, the effect of dissolved oxygen concentration on the corrosion rate of cast iron specimens was evaluated. The corrosion intensities of cast iron specimens were plotted against the observed dissolved oxygen concentrations disregarding the time of exposure and organisms in the test systems. The function, $Y = 144.2X + 44.3$, ($r=0.8$), represents the data derived from the batch culture studies with microorganisms from the loop systems. Again, the effect of dissolved oxygen on the corrosion rate of cast iron was observed, i.e., when the dissolved oxygen concentration increases, the corrosion intensities also increase generally (Figure 53). During this investigation of batch culture studies, two anomalous results were observed. Test specimens which were exposed to the sterilized loop water for 26 days and the unsterilized loop water for 19 days exhibited higher corrosion rates even though the observed dissolved oxygen in the test menstrums was below 2 mg/l. In addition, the higher decreases in alkalinity were also found in the test menstrums of these systems. More experiments are needed to determine the nature of this observation.

The results of the corrosion intensities of test specimens with loop water suggested that the influence of microbial growth on corrosion rate of cast iron specimens might be more evident as the exposure time progressed. Since the method of corrosion measurement was determined by weight loss analysis during the exposure time increments, it might be that the exposure times examined in this investigation might have been too short to observe any apparent differences between the specimens exposed to test menstrums with and without the microorganisms.

From the results of the microbiological analysis of test menstrums it was postulated that the microbial activities in test menstrums were minimal during the experimental period (up to 26 days).

In the second experiment microorganisms from pipe loop water maintained viability as a mixed culture. With sediment in test menstrum the original concentration of microorganism was sustained even after 26 days of experimental period. The average microbial concentration observed in each test menstrum was 1.7×10^5 per ml.

Bays (114) was of the opinion that microbial populations are directly responsible for enhancing the corrosion process of iron pipes in water distribution systems by changing the pH and Eh in the immediate environment of the pipe wall.

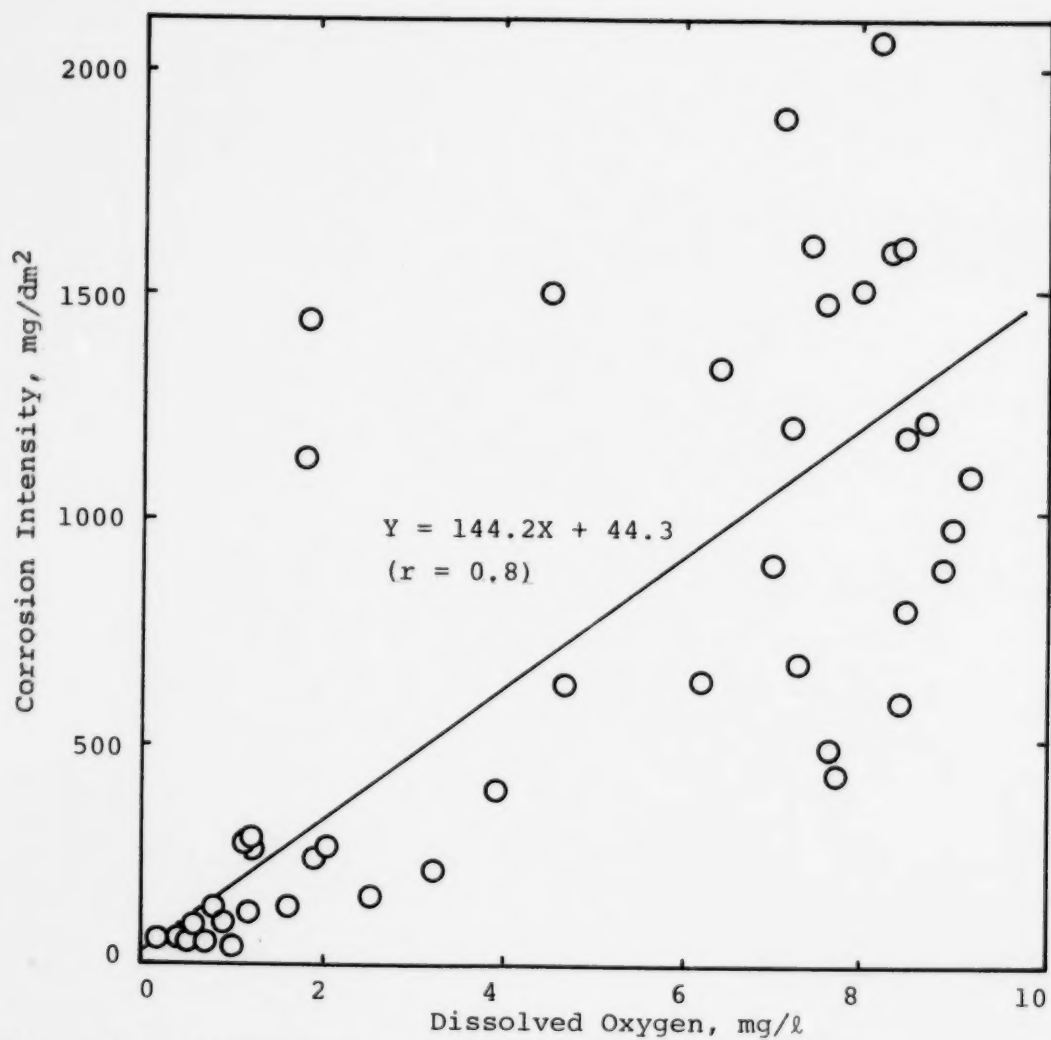


Fig. 53 Dissolved Oxygen of Corrosion Test Menstrums

Results of present investigation concur with Bays's contention that microbial populations influence the corrosion process of iron pipes. The influence of microorganisms on corrosion of iron is evident in inducing localized corrosion of iron metal surface. Microbial activities were limited to micro-environment of metal surface since the test menstrum did not contain high nutrient concentration. Therefore, their influence was a slow process in changing water quality of test menstrums.

As in other batch culture studies, cast iron test specimens exhibited definite localized corrosion.

From the batch culture corrosion studies of cast iron test specimens exposed to pipe loop water with and without the supplementary sediments from the pipe loop system, the following observable conclusions were derived:

- (1) Aquatic microorganisms can maintain viability at the density at which they are normally found in their natural habitat, water distribution system, if the same population mixture is cultured together.
- (2) The dissolved oxygen was the most important controlling parameter in the oxidation of iron. The relative effect on corrosion rate of cast iron exposed to tap water as much larger than any other influence, including that of microbial activity. Over 2000 mg/dm² corrosion intensity of cast iron was observed in system with over 7 mg/l dissolved oxygen, while only 200 mg/dm² corrosion intensity of cast iron was observed in system with less than 2 mg/l dissolved oxygen (26 day exposure).
- (3) In the presence of microorganisms corrosion intensity of cast iron test specimens increased by about 500 mg/dm² for specimens exposed to pipe loop water for 26 days. Corrosion intensities of cast iron test specimens exposed to pipe loop water less than 10 days did not show any difference between systems with and without the loop water organisms.
- (4) Evidences of localized corrosion on cast iron test specimens in the presence of microorganisms were clearly seen in this study. It might be that the primary role of microorganisms on corrosion of pipe walls in the distribution system might be that localized corrosion on pipe surfaces with possible "pits" in pipe mains.
- (5) The changes in alkalinity were observed in all test

menstrums. Decrease in alkalinity was attributable to the formation of ferrous carbonate between oxidized iron and bicarbonate ion in test menstrum.

SECTION 9

EVALUATION OF EFFECTIVENESS OF CORROSION CONTROL BY POLYPHOSPHATE ADDITIONS

INTRODUCTION

Corrosion in a water distribution system is a perennial problem faced by water utilities. If corrosion is not checked, costly main replacements are inevitable. Also, corrosion may deteriorate the water quality and decrease the hydraulic capacity of the pipes by causing pipe wall pitting and the growth of tubercles. In the past, the addition of phosphate compounds to water has been used in many public water supplies as a means of corrosion control. However, our understanding of this corrosion control method is still rather fragmentary, especially regarding the relative effectiveness of this chemical treatment and its subsequent impact on water quality.

Several different commercial phosphate formulations, including Fisher Scientific's sodium metaphosphate, Monsanto's sodium hexametaphosphate, Olin's sodium hexametaphosphate and Calgon's C-8, C-39 as well as TG-10 zinc polyphosphates were selected for study in this investigation.* These compounds were selected on the basis of their use in water utilities.

The specific objectives for this study were to determine: 1) the effectiveness of various dosages of different phosphate compounds on corrosion control; 2) the effect of dissolved oxygen, pH, total alkalinity and calcium concentrations on corrosion inhibition by these compounds; 3) chemical changes in test system water as a result of phosphate additions; 4) the effect of phosphate additions on stimulating microbiological growth; 5) the effect of various dosages of phosphate, total alkalinity, and calcium hardness on the formation of protective coatings; 6) the correlation between the corrosion rate of cast iron test specimens and the internal galvanic current flows; 7) the mechanism of corrosion inhibition by phosphate additions.

*Description and other details of these commercial formulations are in Appendix C.

Materials and Methods

In accordance with the objectives of this investigation, laboratory experiments were designed to examine the utility of phosphates for corrosion control in water distribution systems. The description of each laboratory investigation follows:

A. Batch Corrosion Test Systems Studies

Phosphate compounds examined during batch corrosion test studies included several commercial phosphate products mentioned earlier.

A galvanic corrosion test system using cast iron (Size 7.8 x 2.2 x 0.2 cm) and copper (Size 7.8 x 2.2 x 0.05 cm) specimens with a copper wire bridge in a plexiglass tank was used for this study. The batch corrosion test system is shown in Figure 54. Cast iron test specimens, cut from a pipe which was removed from a distribution system, were selected to represent a material that is used in water distribution systems. The cast iron specimen preparation included milling and grinding to obtain a homogeneous surface. The specimens were then soaked in acetone for about 3 minutes to remove any grease and oil before using in the test.

The purpose of this galvanic setup was to speed up corrosion process which occurs in anodes (cast iron specimen). The batch corrosion studies were initiated by adding a known amount of test chemical into each separate tank (Size 20 x 20 x 30 cm) which contained ten liters of test water. Mixing was continuously provided by a magnetic mixer and stirring bar. Water quality parameters in the tank were measured at periodic intervals. These parameters included temperature, pH, total alkalinity, total hardness, calcium hardness, total iron, orthophosphate, total phosphate, dissolved oxygen (D.O.), turbidity and standard plate counts (SPC). In addition, after seven days of operation, the cast iron test specimens were removed to determine the weight loss, (expressed as corrosion rate, milligram per decimeter square per day (mdd) by using the procedures presented in ASTM Standard G31-72 (104).

In general, the methodology for most of these analyses were performed in accordance with procedures outlined in Standard Methods (95). Dilute sulfuric acid (0.02N) and EDTA(0.02N) titration methods were used to measure total alkalinity, total hardness and calcium hardness, respectively. The Ferrozine Method (99) was used to measure total iron concentration. This procedure was used because of its simplicity. In addition, it appears to be more accurate than 1,

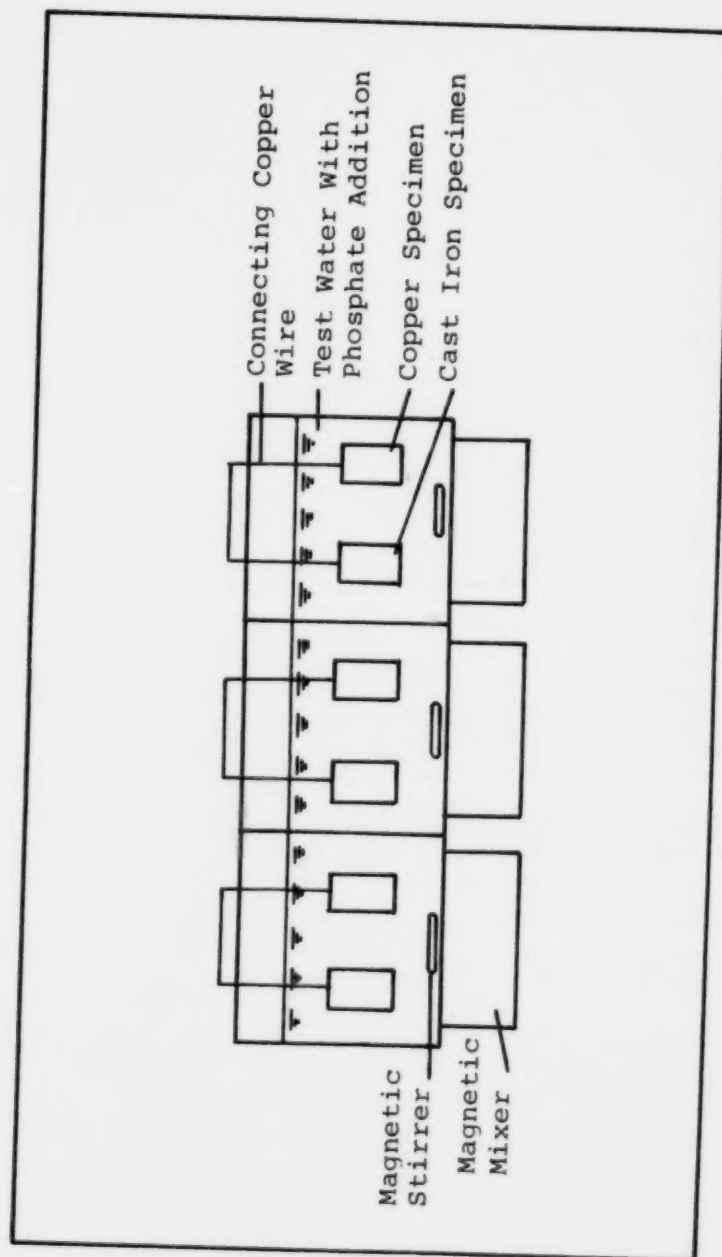


Fig. 54 Batch Corrosion Test System

10 phenanthroline method in determining low concentrations of iron in water. The ascorbic acid reduction method was employed to measure the orthophosphate and total phosphate concentrations. The Winkler method and the dissolved oxygen probe were used to measure the dissolved oxygen concentrations in test water. Hach's turbidimeter was employed to measure turbidity. Microbiological analysis of standard plate counts was performed on the Standard Method Agar at 35°C incubation for two days. Generally, water samples were analyzed as soon as they were collected from the corrosion test systems. Occasionally, water samples were refrigerated at 5°C, if analysis could not be conducted immediately.

The batch corrosion studies included the following investigations:

1. The effects of various phosphate compounds and phosphate dosages on corrosion.
2. The effect of pH and total alkalinity on corrosion in presence of the optimum phosphate dosage.
3. The effect of calcium hardness concentration on corrosion in presence of the optimum phosphate dosage.
4. The effect of dissolved oxygen concentration on corrosion in presence of the optimum phosphate dosage.
5. The chemical compositions of protective coatings on both cathode and anode metal surface.
6. The chemical changes occurring in solution during the test period, including changes in pH, total alkalinity, calcium, total hardness, turbidity and phosphates.

B. Continuous-flow Water Corrosion Test Systems Studies

Continuous-flow water corrosion studies were undertaken following the batch corrosion studies. This laboratory scale continuous-flow water system was constructed to simulate a water distribution system. During the test, the University of Missouri-Columbia laboratory tap water was introduced into a constant-head inlet reservoir (Size 45 x 45 x 45 cm). The water then entered three separate tanks at a flow rate of about 220 ml per minute. The contents of the tanks were continuously mixed by magnetic mixers and stirring bars. Different concentrations of phosphates were added to the influent water and these tanks by metering pumps. The phosphate stock solutions were prepared daily. Then the treated water was introduced into three separated specimen holders (Size 45 x 20 x 20 cm) where six pairs of galvanic corrosion cells (cast iron and copper test specimens connected with copper wire) were

suspended in water. An orifice with manometers was used for measuring the water flow rate. Also, an outlet reservoir was provided for flow control and to ensure a full flow condition in the water system. The entire experimental apparatus was covered with either aluminum foil or black plastic to prevent algal growth. The flow of the water through the system over a period of time eventually caused test specimens corrosion and water quality changes. A schematic of the apparatus utilized for this study is shown in Figure 55 .

Water samples were routinely taken at the sampling points shown in Figure 55 . Chemical and microbiological analysis of the water samples included: temperature, pH, total alkalinity, total hardness, calcium hardness, total iron, dissolved oxygen, turbidity and standard plate counts. In addition, the rate of weight loss of cast iron test specimen with time was also determined. The same methods of analyses were employed as described in the previous section on batch corrosion studies.

C. Particles Formation Studies

Based on literature review, it was believed that polyphosphate corrosion inhibition functions by depositing (or precipitating) a continuous adherent thin coatings on metal surface which protects it from the corrosive water. Unfortunately, it was found very difficult to conduct experimental insolubilization (precipitation) studies for a metal with such a small solubility (less than $10^{-6}M$) due to the limitation of analytical instruments. Instead, attempts were made to determine the particles and their characteristic size distribution in the phosphate-enriched test water in order to give light to the characteristics of metal phosphate precipitates. A HIAC-320 12-channel automatic particle counter was utilized to provide particle size distribution data. Using the light blockage principle, the HIAC particle counter measures the maximum projected area of a particle as it passes across the measuring zone. During this study, HIAC-300 particle size sensor, with detection limits of 5 to 300 microns was utilized for analysis. Initial studies by using University laboratory tap water (without dilution) and phosphate-enriched water (with dilution) showed that the HIAC counter produced reproducible data. The effect of following factors on particle formation were studied in the batch test systems:

1. The effects of various phosphate dosages (Calgon TG-10)
2. The effects of various calcium concentration at a constant phosphate dosage (20 mg/l as P_2O_5) and
3. The effects of total alkalinity at a constant phosphate dosage (20 mg/l as P_2O_5).

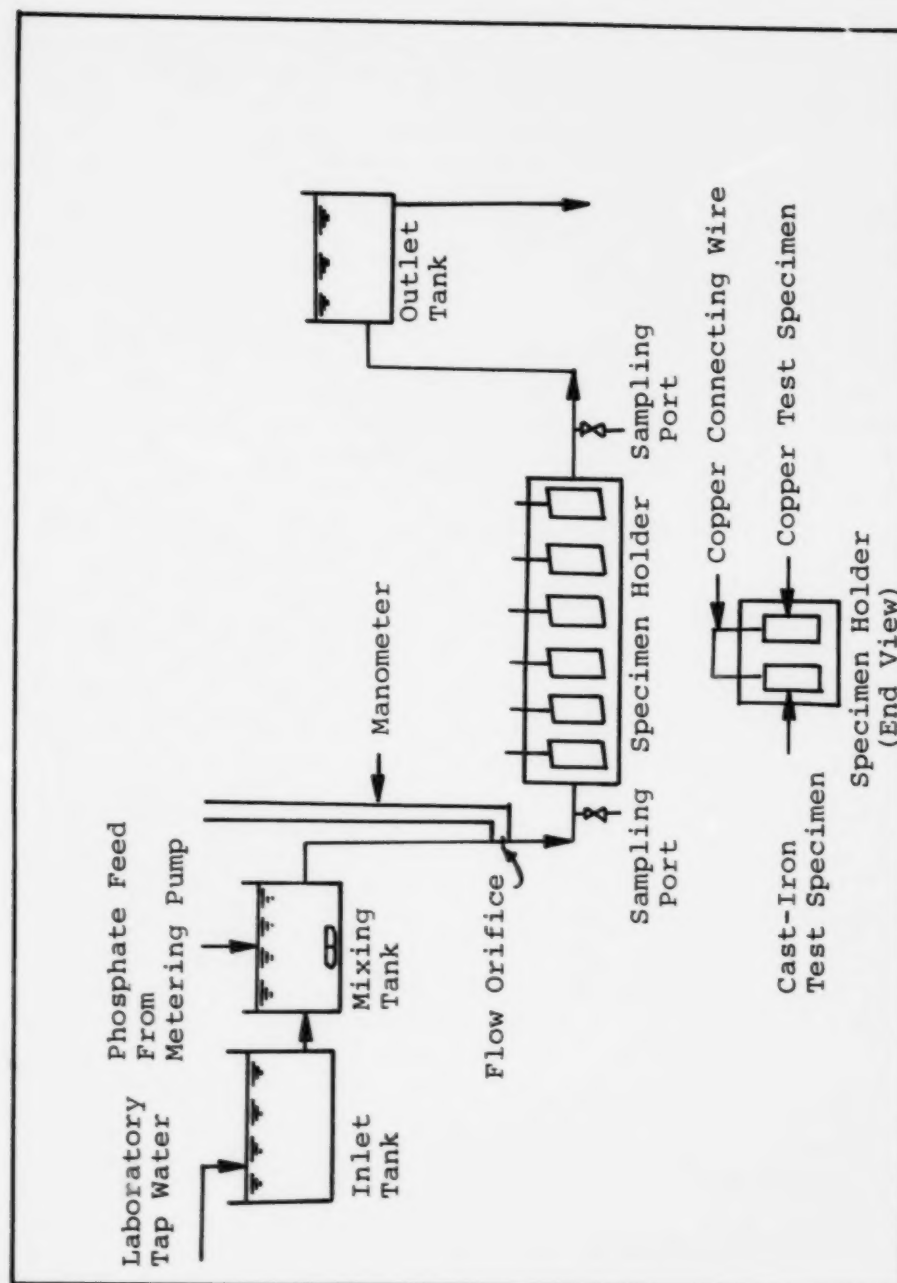


Fig. 55 Continuous-Flow Corrosion Test System

D. Galvanic Current Studies

In order to further understand corrosion inhibition with the addition of phosphate compounds, galvanic current measurement across the galvanic cell were initiated. It was expected that short term measurement of galvanic currents could serve as an immediate indication of corrosion rate in the test system. For this study, a Simpson 270 Series 3 Taut Band volt-ohm-milliammeter was utilized. This device was used to measure the short-circuit currents between two electrodes (cast iron and copper test specimens) of the galvanic cells. The current measurement began by disconnecting the copper wire conductor periodically which normally connected the galvanic cell of corrosion test systems. The two separate copper wires were then connected to the ammeter, and the galvanic current was measured. After measuring the current flow, the cells were re-connected again immediately.

E. Phosphate Recovery as a Function of Hydrolytic Digestion Time in Autoclave

Studies were undertaken to determine whether 30 minutes of persulfate hydrolytic digestion time for the reversion of condensed phosphates to orthophosphates as suggested by Standard Methods (95) was appropriate for the measurement of commercial phosphate products by the ascorbic acid method. It must be noted that persulfate digestion is the less tedious method among the three techniques presented in Standard Methods. However, it was found that in the persulfate procedure the phosphate readings from spectrophotometer were not stable. Therefore, this method was modified to give a better stability. The details of the modifications are presented in reference (115).

Sodium metaphosphate (Fisher Scientific), sodium hexametaphosphate (Monsanto) and sodium-zinc phosphate glasses (Calgon TG-10) were chosen for this particular study. Synthetic waters dosed with 20 mg/l as P_2O_5 were prepared with either distilled or University tap water. Magnetic mixer was used to continuously mix the sample during the half hour test period.

The results of experimental test are shown in Figure 56 . Close examination of the data presented shows 30 minutes of digestion time in the autoclave is not sufficient for the measurement of polyphosphates. At 30 minutes of digestion time, percent of polyphosphates or metaphosphate recovery for sodium-zinc phosphate glasses, sodium hexametaphosphate and sodium metaphosphate, were only about 45%, 7% and 32% respectively. If the hydrolytic digestion time were increased to 1 hour, the percentage of phosphate recovery would increase to about 47 to 65%. It was found that, all of the commercial phosphate products studies would be 100% hydrolyzed only after 2 hours

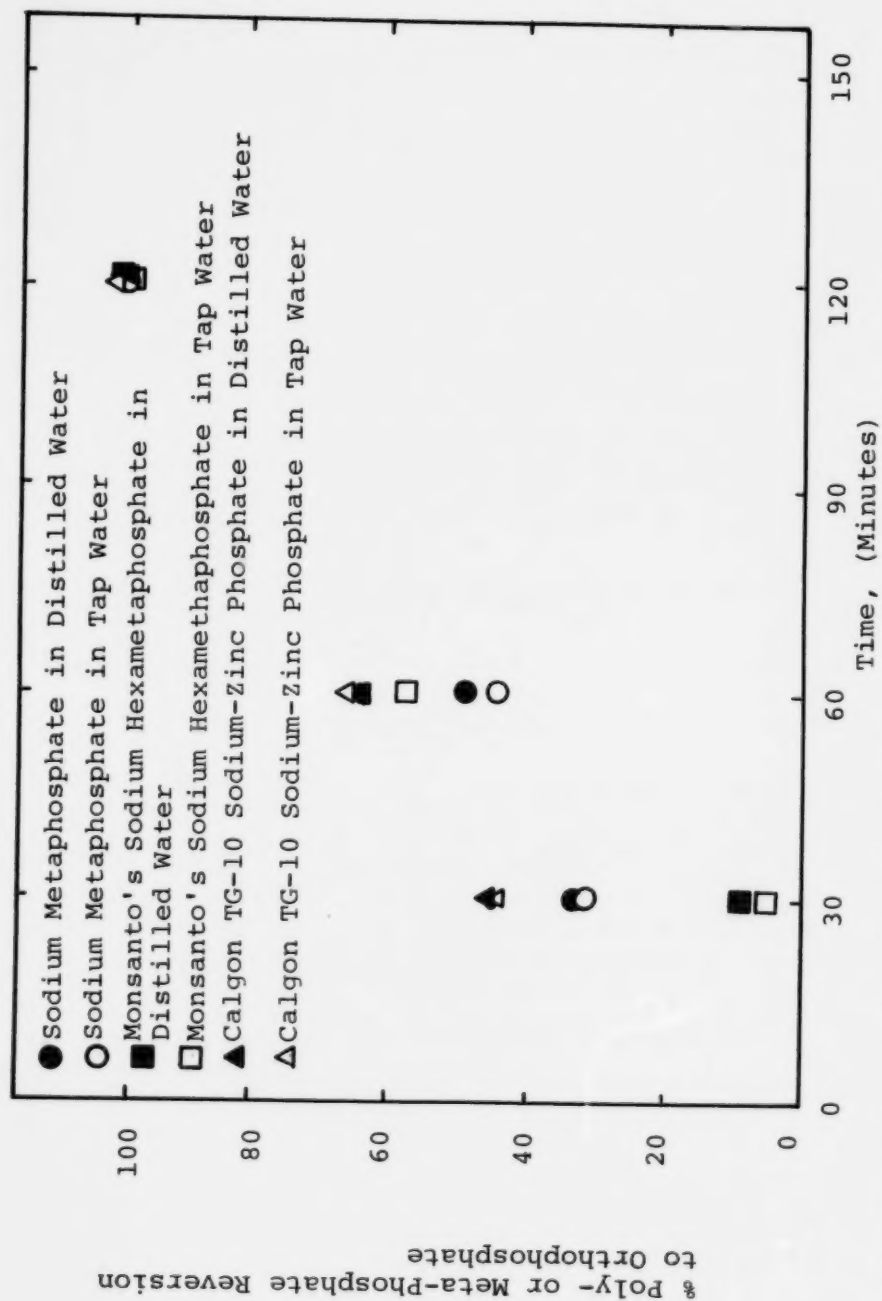
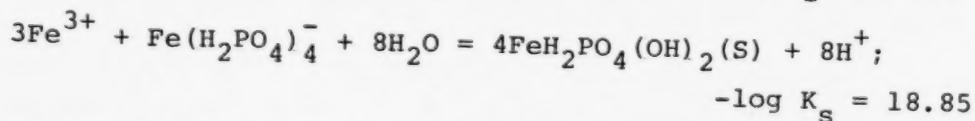
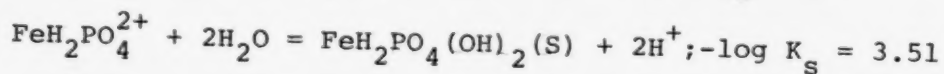
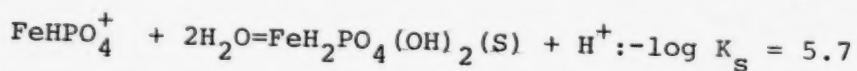
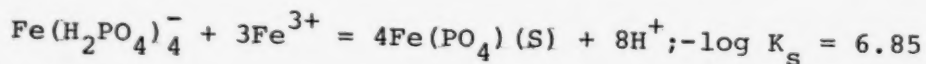


Fig. 56 Reversion of Condensed Phosphate to Orthophosphate (Persulfate Digestion)

of digestion.

F. Evaluation of Ascorbic Acid Method

Sodium-zinc phosphate (Calgon TG-10) was used to evaluate any interference due to the presence of various amounts of iron concentrations on the measurement of condensed phosphate concentrations by the ascorbic acid method. Synthetic waters with three different iron concentrations (0, 1 and 10 mg/l Fe, respectively) and a constant phosphate concentration (9.43 mg/l as P) were prepared with either distilled or University tap water. From the data in Table 86, it can be seen that low concentrations of iron (1 mg/l Fe) did not interfere in the measurement of phosphorus concentrations in both distilled and tap waters. However, it is obvious that relatively low phosphorus recovery resulted from samples containing higher concentrations of iron (10 mg/l Fe). The data on pH also indicated that the increase in iron concentration reduced the pH. The reduction in pH was probably due to some precipitation of ferric phosphate, as shown below:



Most of the waters studied had total iron concentration less than 2.0 mg/l, so the ascorbic acid method for phosphate determination would not be adversely affected.

G. Evaluation of Total Iron Determination

In order to evaluate the effect of various phosphate formulations on the measurement of total iron concentrations by the ferrozine method, the sodium-zinc phosphate galsses were used. Six synthetic waters with six different concentrations of phosphate and a constant soluble iron concentration of 1 mg/l, were prepared with distilled water. The amount of phosphate doses were: 0, 2, 5, 10, 20 and 40 mg/l as P_2O_5 . Figure 57 shows that the total iron concentration of the test waters at various times remained unchanged after 14 days for the different phosphate doses ranging from 2 to 40 mg/l as P_2O_5 . This test showed that the ferrozine method was capable of determining total iron concentration in the presence of various doses of polyphosphate compounds.

Table 86

Effect of Various Iron Concentrations on the Measurement of Phosphorus Concentration by Ascorbic Acid Method

Initial dose of Calgon TG-10 Sodium-Zinc Phosphate 9.43 mg/l as P. Solutions prepared with either distilled water, pH = 5.3, or tap water, pH = 7.7. Mixing time. 0.5 hour, Temperature - 25°C

Test Conditions (mg/l Fe Added)	pH	Total Iron mg/l	P, mg/l		Turbidity N, mg/l
			Ortho.	Total	
Distilled H ₂ O	0	0	0.38	9.25	0.22
	1	0.98	0.38	9.27	0.22
	10	9.88	0.34	8.47	0.27
Tap H ₂ O	0	0.02	0.37	9.00	0.47
	1	0.99	0.34	9.00	2.5
	10	9.88	0.50	8.38	14

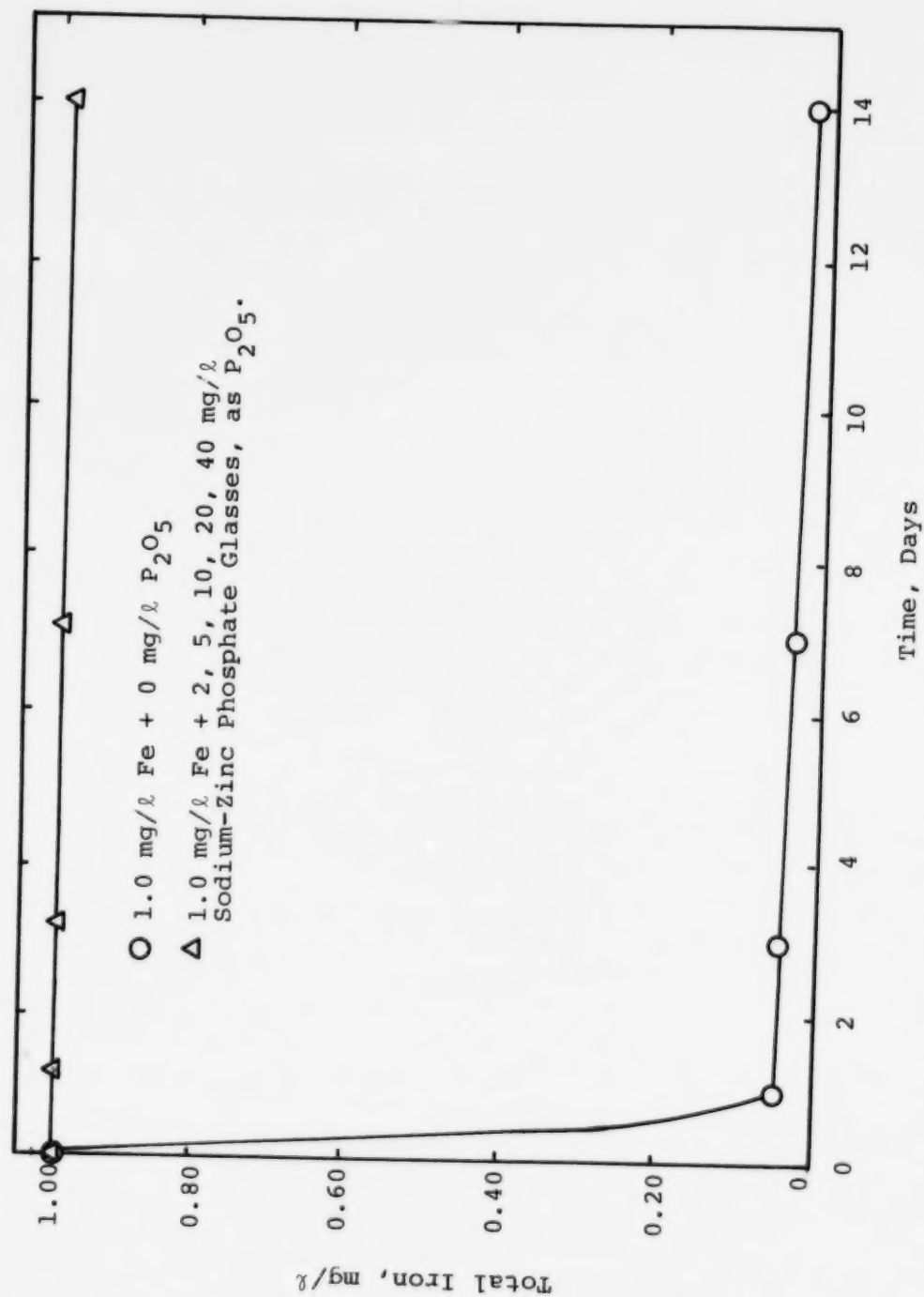


Fig. 57 Effect of Sodium-Zinc Phosphate Additions on the Total Iron Measured by the Ferrozine Method

Results and Discussions

A. Effects of Various Phosphate Compounds and Doses on Corrosion in Batch Systems

A series of corrosion batch tests using University tap water were conducted with the different commercial phosphate products previously described. A plot of the effect of phosphate formulations on corrosion of cast iron test specimens in galvanic batch systems is shown in Figure 58 .

The effect of adding small quantities of phosphate compounds on the corrosion of cast iron specimen was tested. In the first four tests, a galvanic corrosion test system as described earlier, was used. The phosphate dosage was varied between 0 to 10 mg/l as P_2O_5 . These low phosphate dose ranges are commonly used in water distribution systems. In Figure 58 , the corrosion rate data shows that small quantities of phosphates produced no metal corrosion inhibition. In fact, they appear to have accelerated the corrosion rate by a factor of two compared to the control during the seven days of the test period. In a subsequent test, corrosion studies were conducted using a non-galvanic cell. Figure 59 shows the results of corrosion inhibition by phosphate compound in a non-galvanic test system. As expected, the corrosion rate of the cast iron specimen in the non-galvanic cell was less than that in the galvanic cell. However, the addition of phosphate dosage up to 5 mg/l as P_2O_5 still did not show corrosion inhibition.

In the next test, the pH of the test water was reduced approximately to 5 using hydrochloric acid. Phosphate (Monsanto's sodium hexametaphosphate) additions of 0, 0.75 and 1.5 mg/l as P_2O_5 , respectively, were made to the test waters. It appears that the rate of phosphate hydrolysis was faster than in all previous tests. As a result, less condensed phosphate remained to provide protective coatings. In addition, these phosphate dosages did not provide corrosion protection to the metal under the test conditions, i.e., pH = 5.

The appearance of the cast iron test specimens and its deposits changed with time of exposure to the test water. It generally changed color from black-green to yellow-orange with time. However, there was no difference between the low-phosphate enriched solution and the control. They appeared to be covered with a uniform thick yellow-orange layer that had very poor adhesion to the metal. The layer was found to be even thicker when the pH of the solution was dropped to 5. However, in most cases, copper test specimens appeared to be unchanged except for losing their shiny appearance.

In general, a stimulation of cast iron specimen corrosion rate in galvanic test systems was found in all experiments

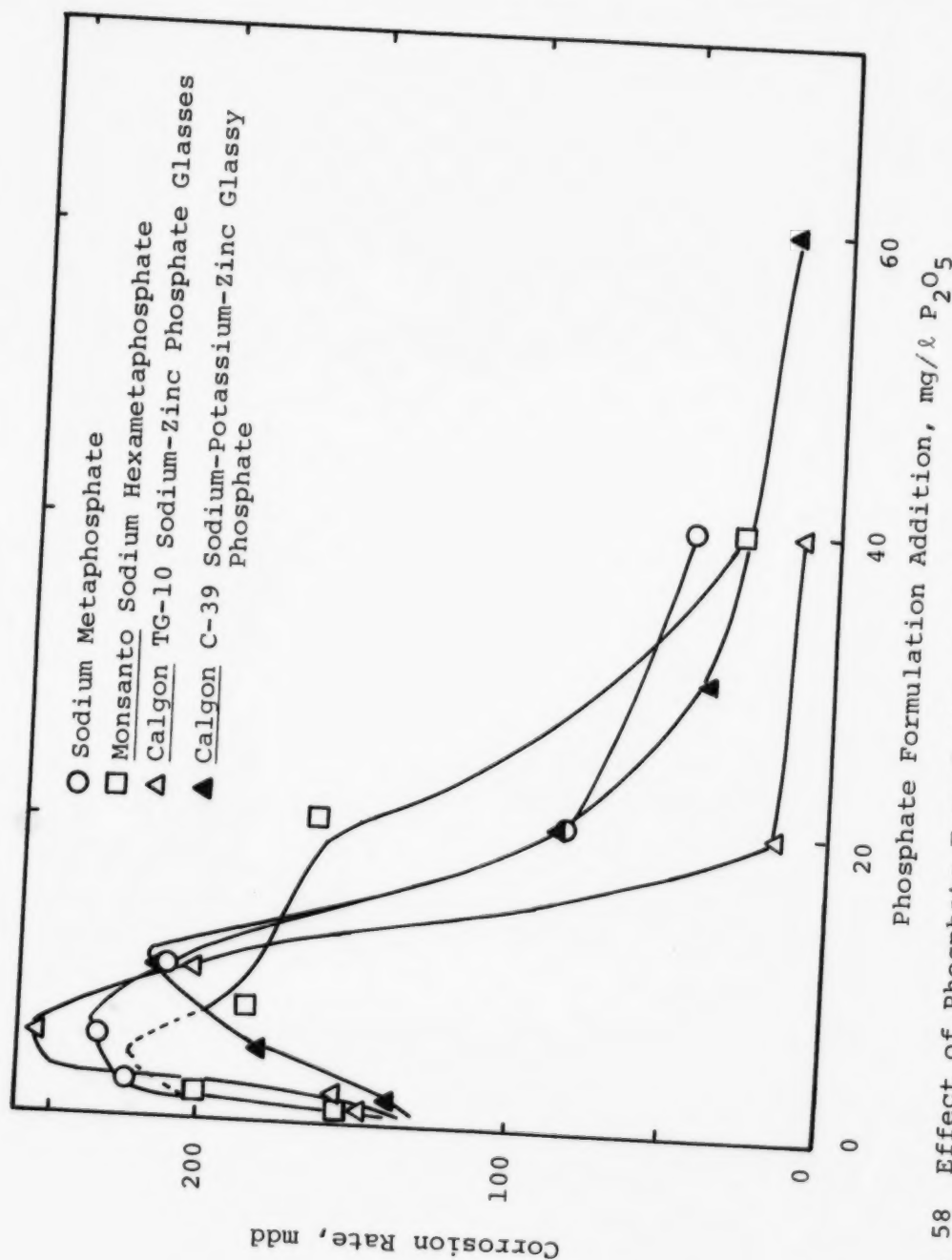


Fig. 58 Effect of Phosphate Formulation Additions on Corrosion of Cast Iron Test Specimens in Galvanic Batch Systems

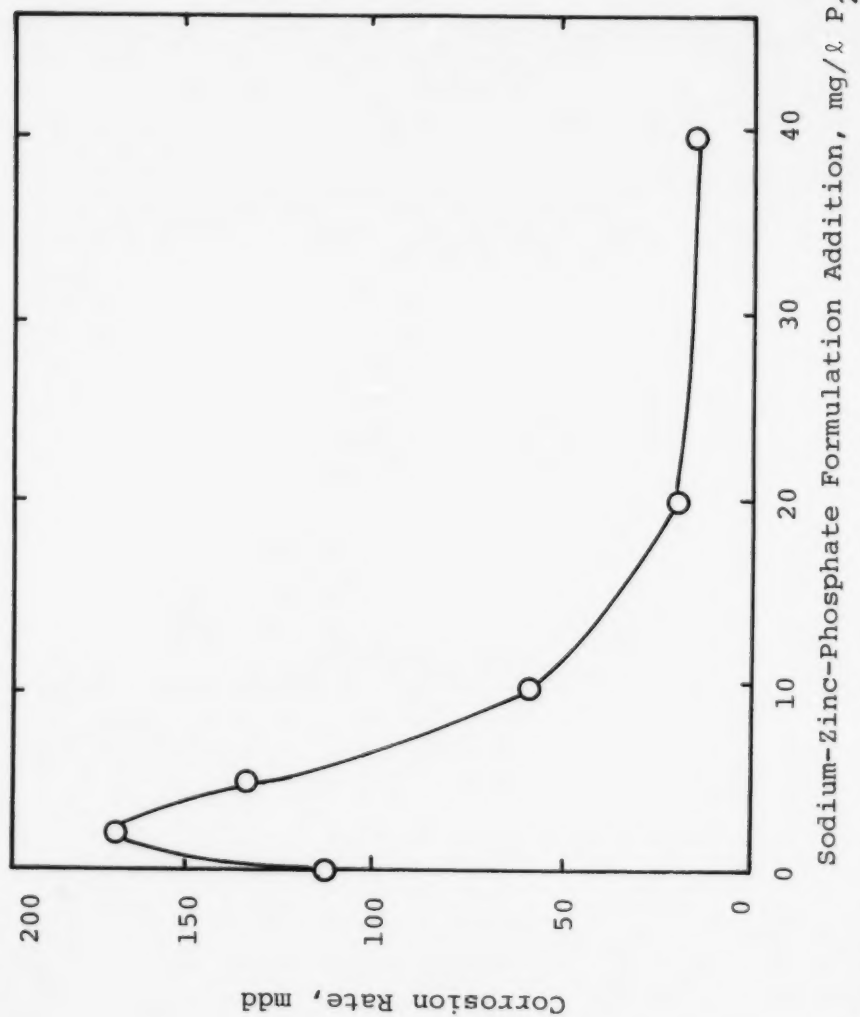


Fig. 59 Effect of Addition of Sodium-Zinc, Glassy Phosphate (Calgon TG-10) on Corrosion of Cast Iron Test Specimens in Non-Galvanic Batch Systems

using different commercial phosphate products up to phosphate dosages of 10 mg/l as P_2O_5 . For non-galvanic test systems, a stimulation of cast iron specimen corrosion rate was found in phosphate dosages up to 5 mg/l as P_2O_5 . This corrosion stimulation may have been due to the sequestration of the calcium by small quantities of phosphates. Calcium sequestration may have prevented the deposition of a protective coating of calcium carbonate on the cast iron test specimen.

Having completed these initial studies of the effect of small quantities of phosphates, efforts were then made to examine the effect of higher concentrations of phosphate compounds. It was expected that higher phosphate doses would provide corrosion protection not obtained at the low doses. These results for systems with galvanic cells shown in Figure 58, indicate that the addition of 20 mg/l P_2O_5 and greater of sodium metaphosphate, Calgon C-39 and Calgon TG-10, decreased the corrosion rate of the cast iron specimens very significantly. However, this corrosion reduction was not seen in Monsanto's sodium hexametaphosphate until 40 mg/l as P_2O_5 had been added. In Figure 58, among the several commercial corrosion control products, the zinc polyphosphates appeared to be most effective. The zinc ions may have enhanced the formation of the protective coatings. On the other hand, for systems with non-galvanic cells shown in Figure 59, indicated that the addition of 10 mg/l as P_2O_5 and greater, of Calgon TG-10 sodium-zinc phosphate, decreased the corrosion rate of the metal specimens very significantly.

The University tap water is saturated with respect to calcium carbonate. To conduct experiments in a system which was unsaturated with respect to calcium carbonate, synthetic waters were made from distilled water by adding the following ingredients:

Synthetic Water Composition

Chemical	Concentration (mg/l)	Ion Concentration (mg/l)				
		Mg ²⁺ *	Ca ²⁺ *	SO ₄ ²⁻	Cl ⁻	Alk*
MgSO ₄ · 7H ₂ O	37.0	15		14.4		
CaCl ₂ · 2H ₂ O	44.0		30		21.2	
NaHCO ₃	50.4					30

*Calcium ion, magnesium ion and alkalinity expressed as mg/l $CaCO_3$.

The effect of phosphate concentrations (Calgon TG-10, sodium-zinc phosphate glass) on the corrosion rate of cast iron test specimens in water unsaturated with respect to calcium carbonate was evaluated at six different levels, 0, 0.5, 2, 5, 10 and 20 mg/l as P_2O_5 . Figure 60 shows that the phosphate addition did not decrease the corrosion rate of cast iron specimens until a certain amount of phosphate had been added to both unsaturated and saturated states of calcium carbonate. During the seven-day test period, total alkalinity and calcium hardness in the calcium carbonate unsaturated waters remained unchanged.

From these results, it can be summarized that the use of small quantities of various commercial phosphate compounds may increase the corrosion of cast iron pipes in water distribution systems. As mentioned earlier, this may be due to sequestration of the calcium ion by small quantities of phosphates, thereby preventing the deposition of a protective coating of calcium carbonate on the cast iron test specimen. When phosphate dosages were increased to 20 mg/l P_2O_5 and greater, protective coatings on metal surfaces may have been formed preventing corrosion. This assumption is consistent with the appearance of the surface of the test specimens. Although cast iron test specimens tended to have a small area of localized corrosion, copper test specimens were covered with uniform thin yellow-white coatings. It appears that the protective coating which forms on cathodic areas decrease the corrosion rate of cast iron test specimens in water by increasing the degree of cathodic polarization in the corrosion cells. In practice, an initial high polyphosphate treatment of 20 mg/l P_2O_5 at pH 8.0 may provide an initial protective coating for corrosion inhibition. After an initial high dosage, small quantities of phosphate dosage (about 1-2 mg/l P_2O_5) may be sufficient to maintain the protective coatings.

Figures 61 and 62 show the changes of total iron concentration during the first ten hours in several corrosion experiments. In most cases, the total iron concentration in solution could be linked to the corrosion rate of cast iron test specimens. The more total iron released into solution, the more corrosion had occurred in the cast iron test specimens. Thus, the initial changes in total iron concentration in the test system can indicate if sufficient corrosion inhibitor had been added or not.

B. Effect of pH and Total Alkalinity on Corrosion in Presence of the Optimum Phosphate Dosage

In order to study the influence of pH and total alkalinity on corrosion control by phosphate compounds in batch systems, synthetic waters were prepared from distilled water using sodium bicarbonate as a source of alkalinity, calcium chloride as a source of calcium and magnesium sulfate as a source of

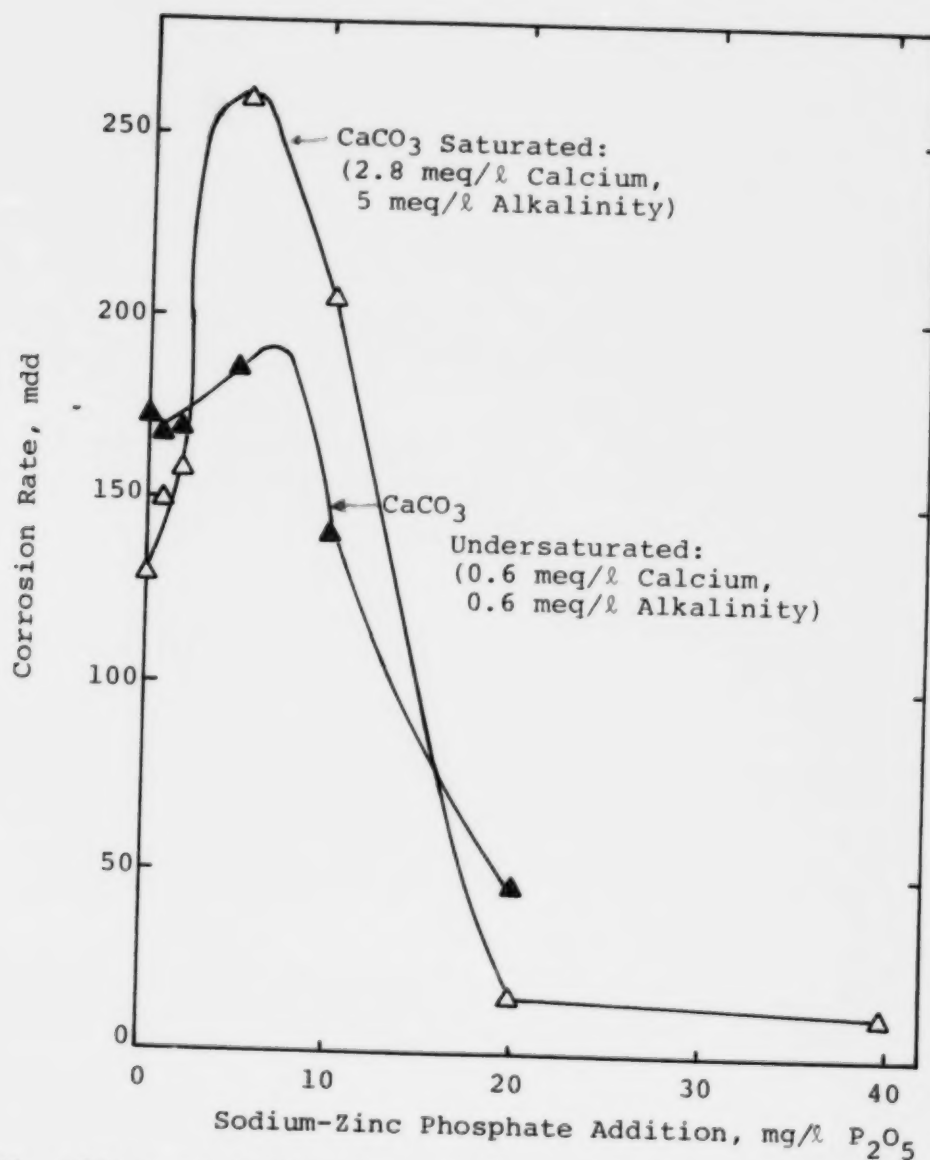


Fig. 60 Effect of Sodium-Zinc Phosphate Additions on Corrosion of Cast Iron Test Specimens in CaCO₃ Saturated and Unsaturated Solutions.

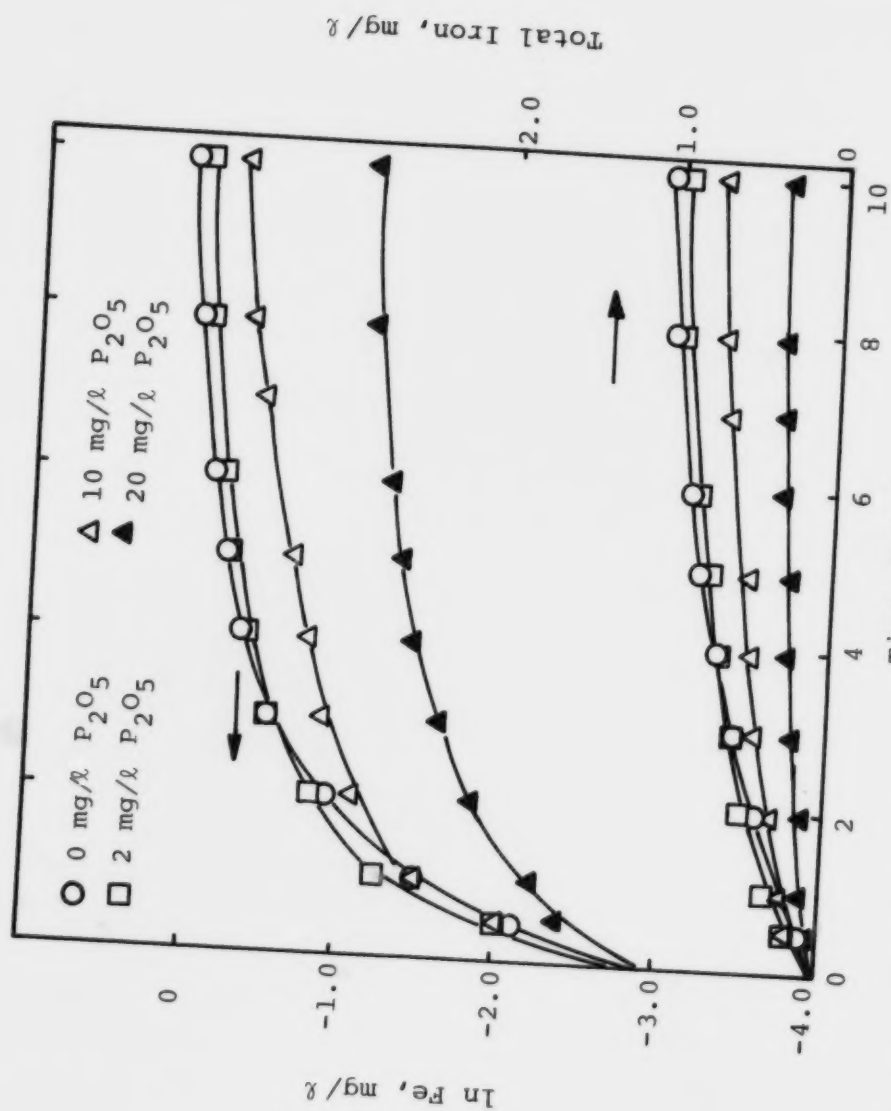


Fig. 61 Total Iron During Galvanic Corrosion With the Addition of Sodium-Zinc-Phosphate, (pH = 7.8)

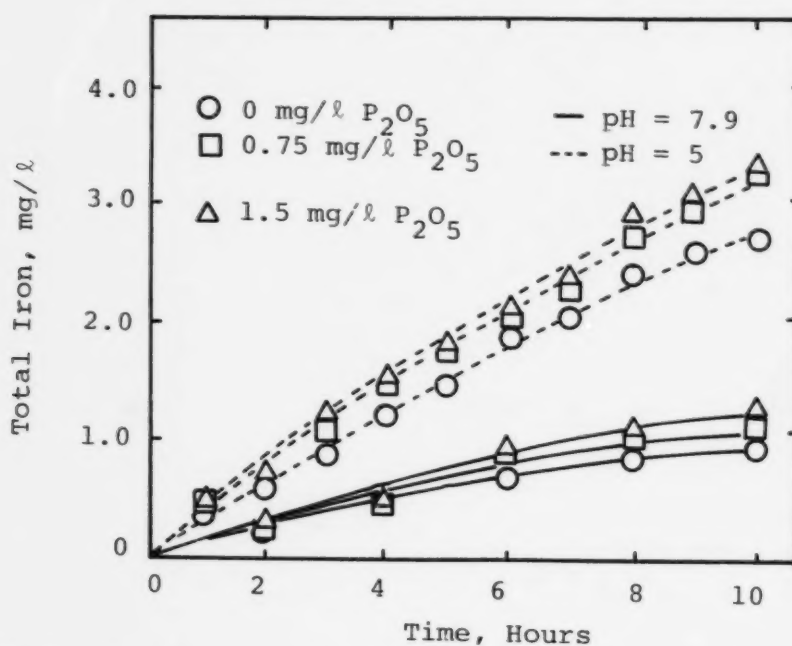
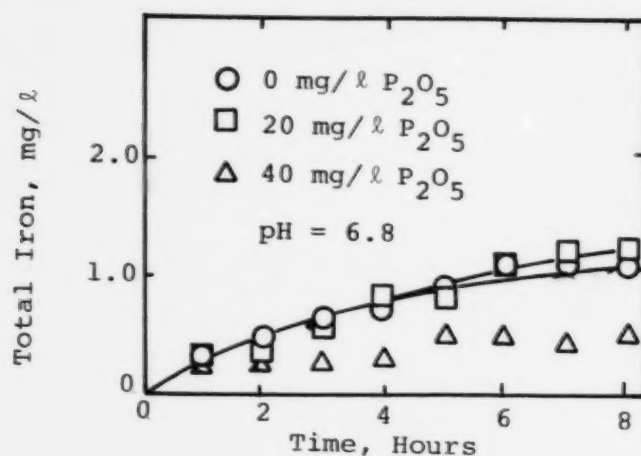


Fig. 62 Total Iron During Galvanic Corrosion With the Addition of Sodium Hexamethaphosphate (Monsanto)

magnesium.

Synthetic Water Composition:

Chemical	Concentration (mg/l)	Ion Concentration (mg/l)				
		Mg ²⁺	Ca ²⁺	SO ₄ ²⁻	Cl ⁻	P ₂ O ₅
MgSO ₄ · 7H ₂ O	89.77	36.4		35.0		
CaCl ₂ · 2H ₂ O	165.98		113.1		80.1	
Calgon TG-10	36.36					20

Ca²⁺ and Mg²⁺ expressed as mg/l CaCO₃

From previous results, it was learned that optimum corrosion inhibition was achieved at a polyphosphate dosage of about 20 mg/l as P₂O₅. The effect of alkalinity variations on the corrosion rate of cast iron test specimens were evaluated at six different alkalinity concentrations, 0, 20, 70, 150, 250 and 500 mg/l as CaCO₃ equiv., respectively. The pH of these synthetic waters were found to be 6.9, 7.7, 8.2, 8.55, 8.75 and 8.9, respectively after seven days test period.

Figures 63 through 65 present data related to the effect of pH and total alkalinity on the corrosion rate of cast iron specimens. Figure 63 shows that increasing amount of total alkalinity and increasing pH tended to decrease total iron concentrations after ten hours. However, in the first three hours no significant differences were observed. The pH values of the six different systems after two hours were 6.8, 7.0, 7.75, 7.8, 7.8 and 7.8 respectively.

Figures 64 and 65 show that the rate of corrosion of cast iron in batch studies, at a optimum polyphosphate dosage of 20 mg/l as P₂O₅, can be somewhat reduced by increasing pH and total alkalinity. This is consistent with the solubility considerations that predict that coatings would be favored by increasing pH values in phosphate-enriched solutions.

Figure 64 shows that the weight of materials accumulated on the cathode increased at lower pH values. Figure 64 also shows an inverse relationship between condensed phosphate accumulated on the cathode and the corrosion rate of the anodic metal. It appears that with increasing pH, the condensed phosphate deposited on the cathode increased the formation of protective coatings. Figure 65 shows a direct correlation between the total weight (mostly iron oxide) deposited on the cathode and the corrosion rate of the anodic metal. However, the decrease in the corrosion rate of metal at high alkalinity may be due to an increased amount of condensed phosphate

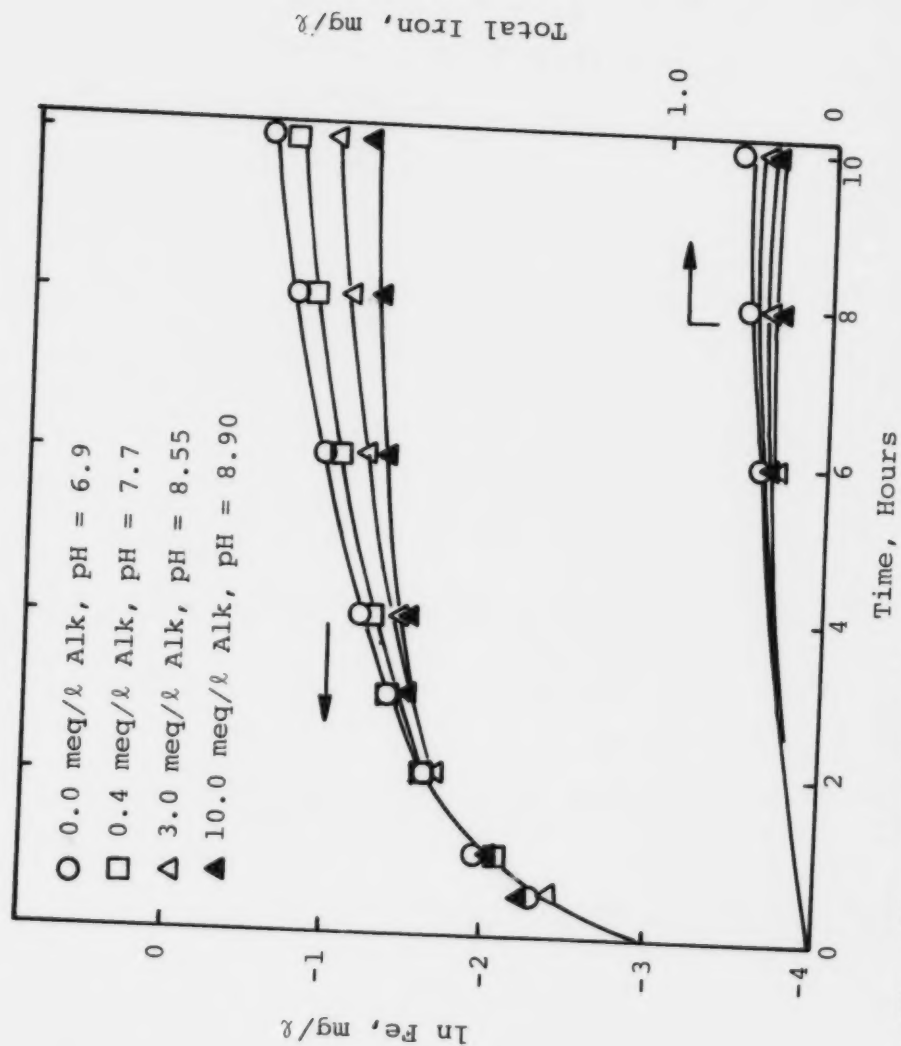


Fig. 63 The Effect of Alkalinity on Total Iron During Galvanic Corrosion in the Presence of Sodium-Zinc-Phosphate (Calgon TG-10)

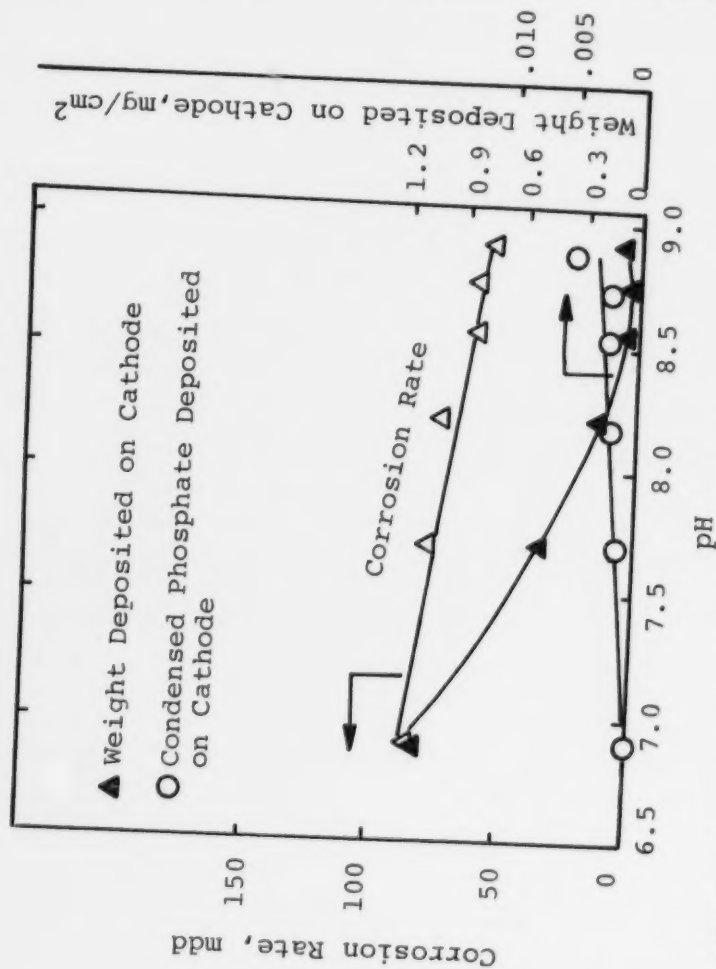


Fig. 64 Effect of pH on Corrosion of Cast Iron Test Specimens in Presence of Sodium-Zinc Phosphate (Calgon TG-10)

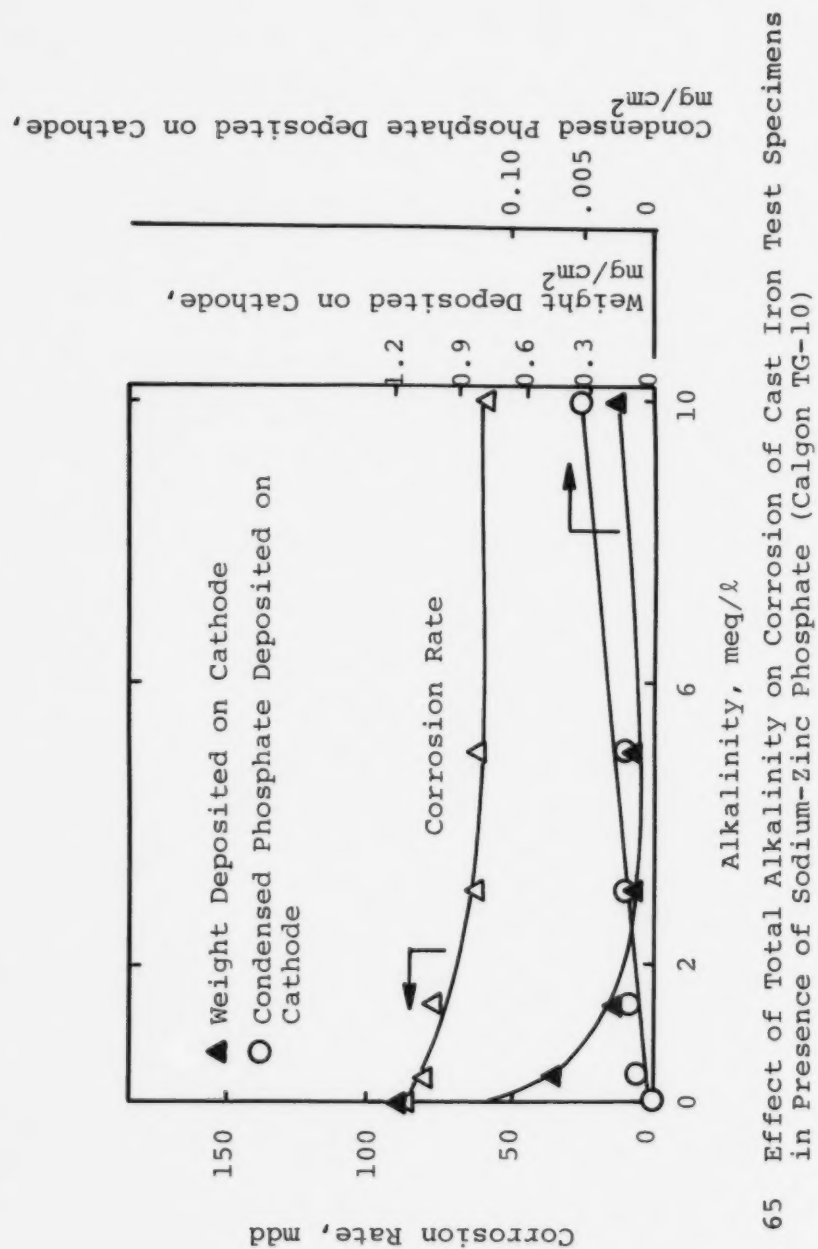


Fig. 65 Effect of Total Alkalinity on Corrosion of Cast Iron Test Specimens in Presence of Sodium-Zinc Phosphate (Calgon TG-10)

deposited on the cathode.

Figure 66 shows an interesting relationship between the hydrolysis of polyphosphate, pH and total alkalinity in a synthetic water after one day of testing. As expected, it shows a relatively high percentage of polyphosphate reversion at lower pH values. As pH values increased to 8.2, the polyphosphate reversion rate decreased.

C. Effect of Calcium Hardness Concentration on Corrosion in Presence of the Optimum Phosphate Dosage

Butler and Owen (92) have reported that calcium ion will react with phosphate to form an insoluble protective coatings in the presence of chloride ion. In the present study to determine the effect of calcium on inhibition of corrosion with phosphates, synthetic waters were prepared from distilled water with calcium chloride, sodium bicarbonate and magnesium sulfate, as shown below:

Synthetic Water Composition:

Chemical	Concentration (mg/l)	Ion Concentration (mg/l)			
		Mg ²⁺	Na ⁺	SO ₄ ²⁻	Alk. P ₂ O ₅
MgSO ₄ · 7H ₂ O	89.77	36.4		35.0	
NaHCO ₃	420.0		115		250
Calgon TG-10	36.36				20

Mg²⁺ and alkalinity expressed as mg/l CaCO₃

The optimum corrosion inhibiting polyphosphate dosage of 20 mg/l as P₂O₅, as determined earlier, was added to test water. The effect of calcium concentration on corrosion rate of cast iron test specimens was then evaluated at six different calcium levels - 0, 20, 70, 130, 260 and 500 mg/l as CaCO₃, respectively.

Figures 67 through 69 present the results of these experiments. Figure 67 shows the effect of increasing the calcium hardness up to 130 mg/l as CaCO₃ on corrosion of iron. Iron concentrations were markedly reduced as calcium concentrations increased. However, increased additions of calcium beyond 130 mg/l as CaCO₃ did not cause any further decrease in iron concentration in the system.

Figure 68 shows that the rate of corrosion of cast iron in batch studies, at an optimum polyphosphate dosage of

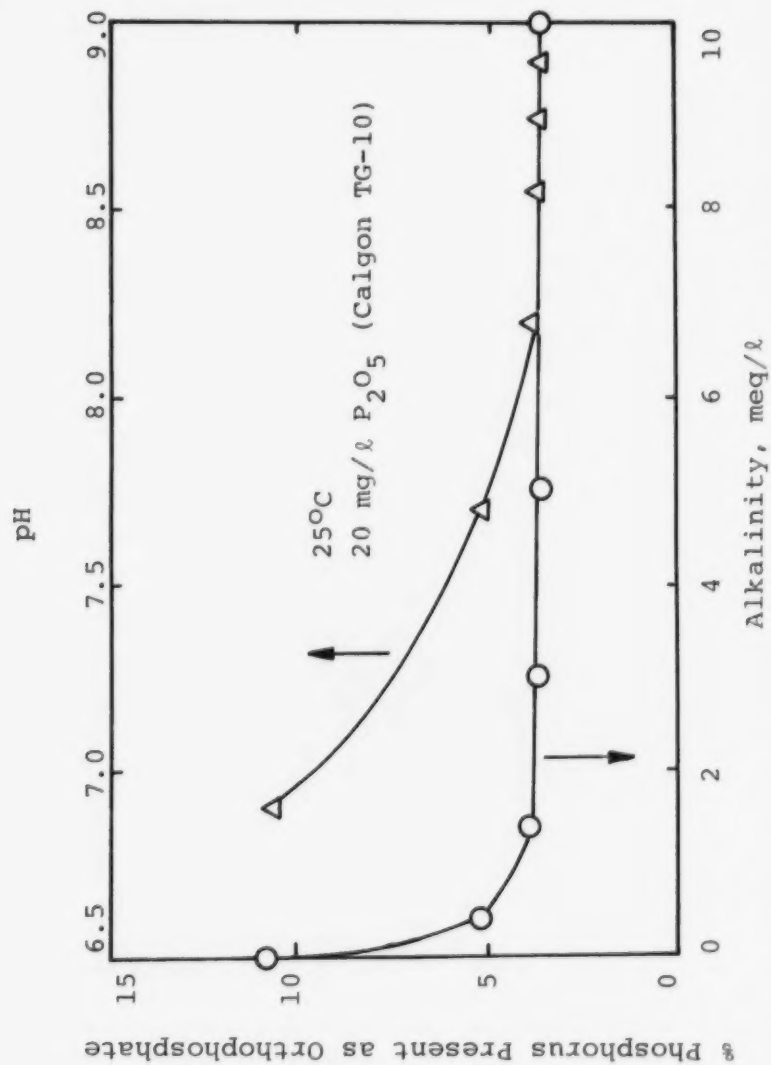


Fig. 66 Effect of pH and Alkalinity on Hydrolysis of Polyphosphate Formulation

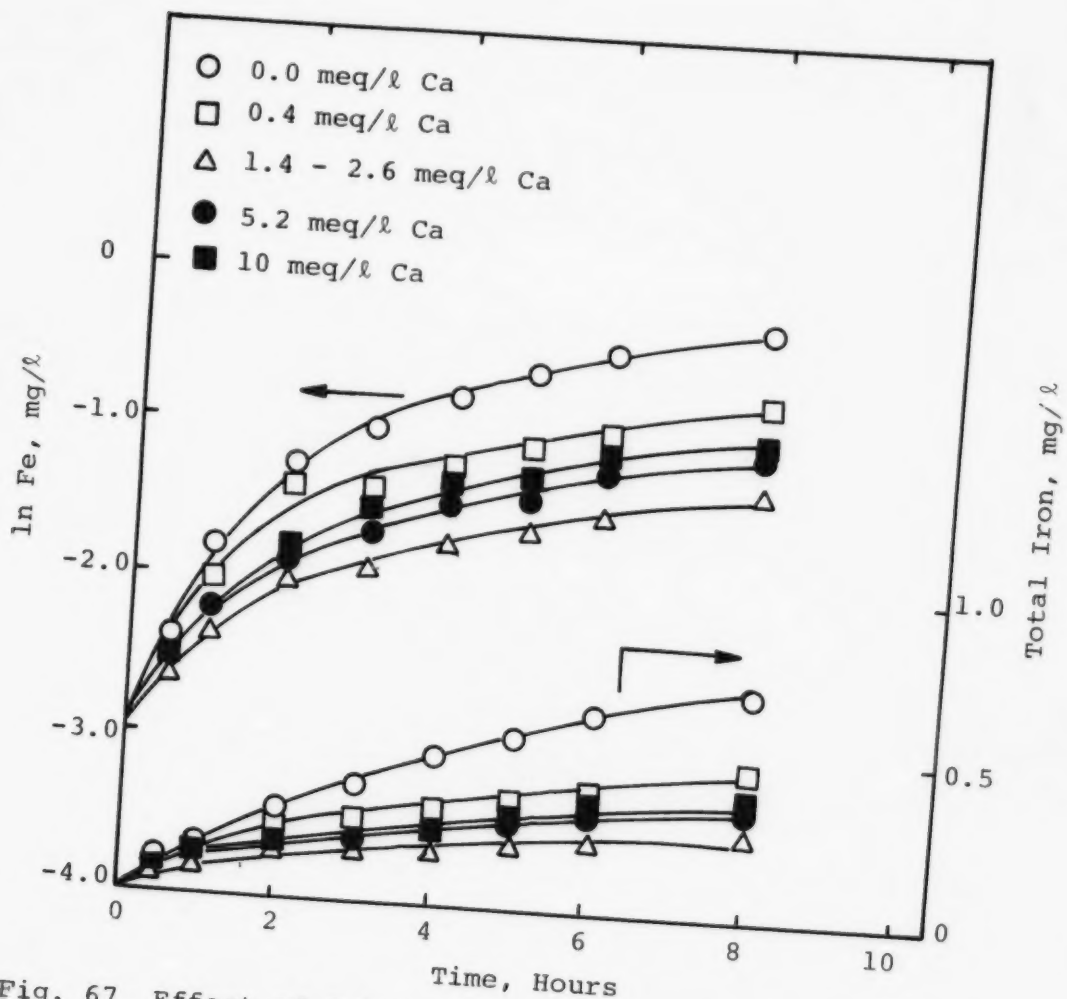


Fig. 67 Effect of Calcium Ion Concentration on Total Iron During Galvanic Corrosion in the Presence of Sodium-Zinc Phosphate (pH = 8.3) (Calgon TG-10)

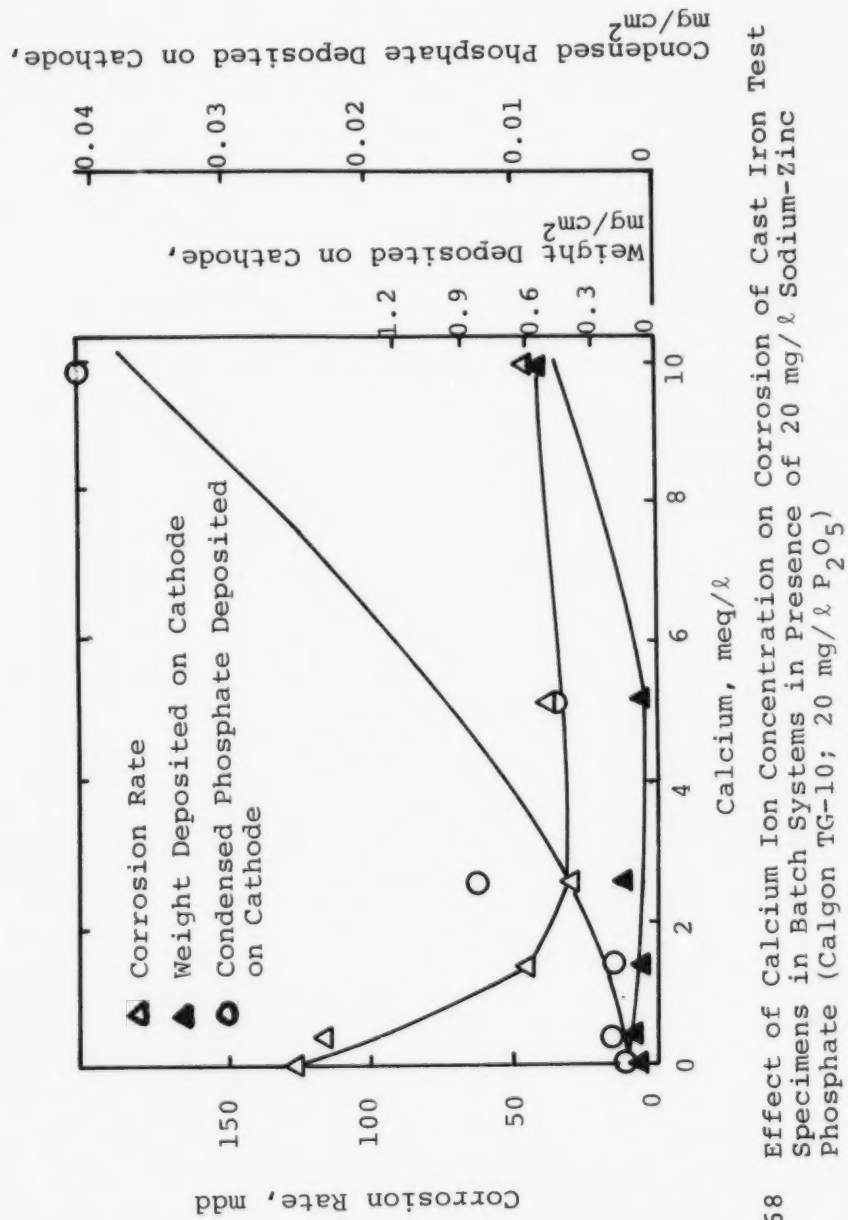


Fig. 68 Effect of Calcium Ion Concentration on Corrosion of Cast Iron Test Specimens in Batch Systems in Presence of 20 mg/l Sodium-Zinc Phosphate (Calgon TG-10; 20 mg/l P_2O_5)

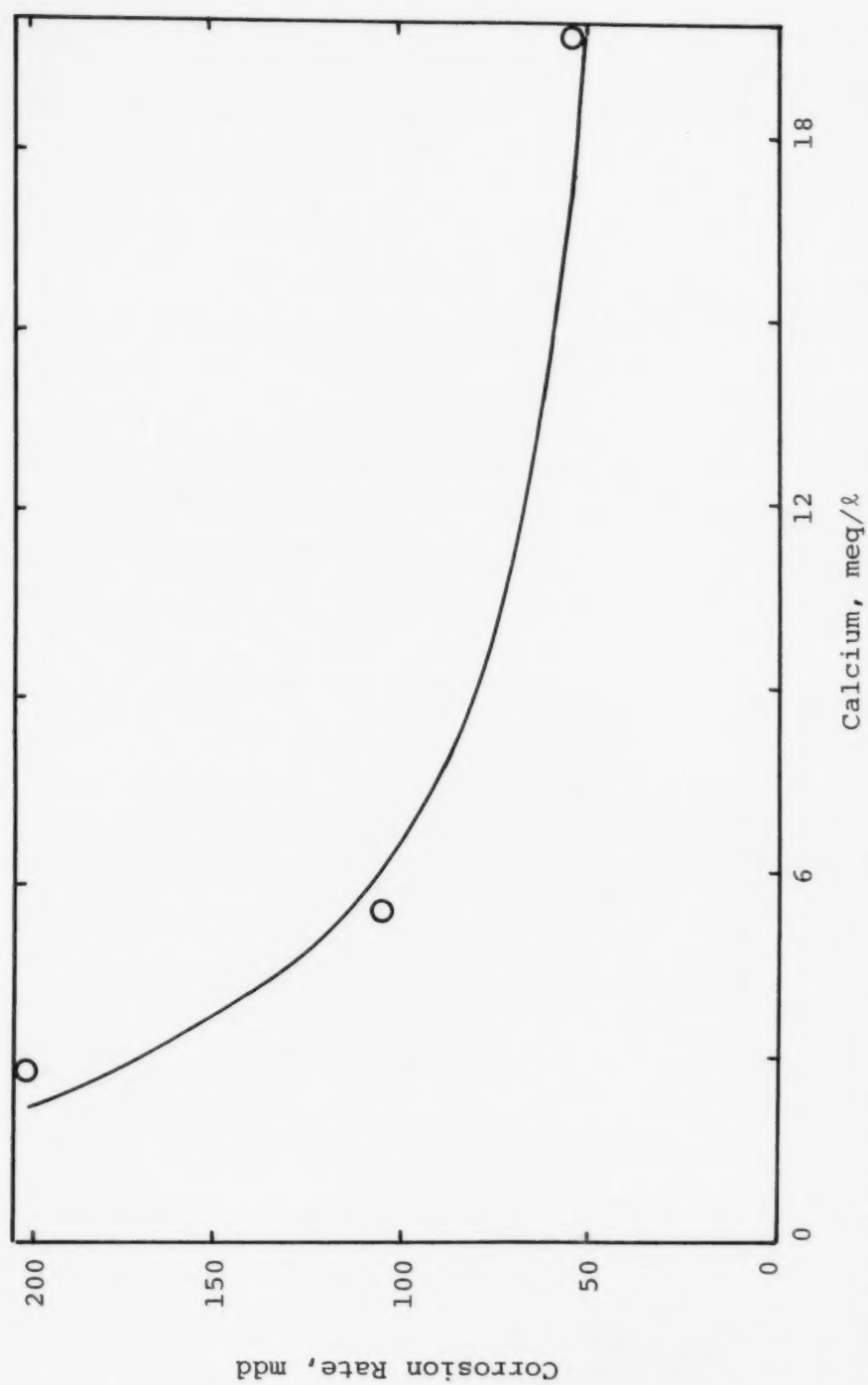


Fig. 69 Effect of Calcium Ion Concentration on Corrosion of Cast Iron Specimens in the Presence of Sodium-Zinc Phosphate (Calgon TG-10; 10 mg/l P_2O_5)

20 mg/l as P_2O_5 , was reduced from 125 mdd to 35 mdd by increasing calcium hardness. Similar results were obtained in tests with 10 mg/l P_2O_5 as shown in Figure 69 .

Figure 68 shows that when the calcium hardness was less than 70 mg/l as $CaCO_3$, the corrosion rate of the anodic metal was inversely related to the calcium ion concentration. In a water having a magnesium hardness of 37 mg/l as $CaCO_3$ and no calcium hardness, the corrosion rate of metal was as high as 126 mdd. This result implies that calcium, specifically, plays the most important role in forming protective coatings during phosphate treatment. Fortunately, most natural waters in the midwestern U.S. contain calcium in excess of 70 mg/l as $CaCO_3$ which would be sufficient to provide a good corrosion inhibition if appropriate amounts of phosphates were added.

Figure 68 shows that the weight deposited and accumulated on the cathode increased with increasing calcium hardness. However, the condensed phosphate accumulated on the cathode showed a marked increase with calcium ion. This is in accord with the theory that the formation of metal phosphate precipitate is favored by increasing calcium concentrations.

Figure 70 shows the hydrolysis of polyphosphate glass as a function of calcium ion concentration after one day. As expected, it shows that the polyphosphate reversion rate increased slightly with increasing calcium ion concentration due to the effect of complexation between calcium ion and phosphate ligand. However, the reversion rate remained very low, about 2 to 4% per day, even in the calcium-enriched solutions.

D. Effect of Dissolved Oxygen Concentration on Corrosion in Presence of the Optimum Phosphate Dosage

Corrosion due to the presence of dissolved oxygen is commonly encountered in water distribution systems since many water utilities use surface supplies as their raw water source, which are generally saturated with oxygen. Moreover, most treated ground water supplies are aerated to remove dissolved gases and to precipitate iron. Theoretically, the important reactions and the standard electrode potentials for the corrosion of cast iron in the presence of oxygen are as follows:

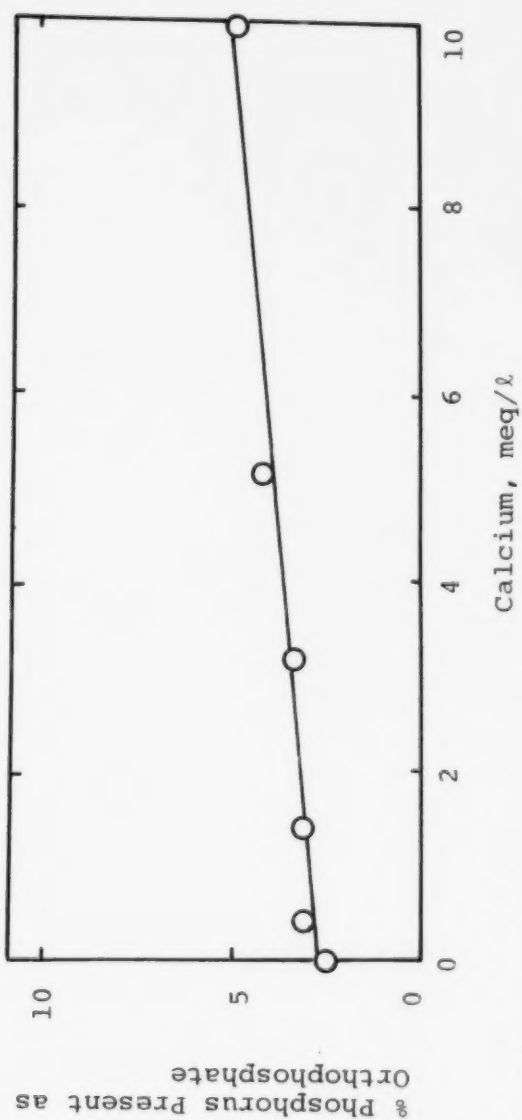


Fig. 70 Effect of Calcium Ion on Hydrolysis of Polyphosphate Compound (Calgon TG-10, 20 mg/l P_2O_5 , 25°C)

	standard electrode potential, V, 25°C
$\text{Fe}^0 = \text{Fe}^{2+} + 2e$	0.44
$\text{O}_2 + 4\text{H}^+ + 4e = 2\text{H}_2\text{O}$	1.229
$2\text{Fe}^0 + \text{O}_2 + 4\text{H}^+ = 2\text{Fe}^{2+} + 2\text{H}_2\text{O}$	1.669
$\text{Fe}^{2+} = \text{Fe}^{3+} + e$	0.77
$\text{O}_2 + 4\text{H}^+ + 4e = 2\text{H}_2\text{O}$	1.229
$4\text{Fe}^{2+} + \text{O}_2 + 4\text{H}^+ = 4\text{Fe}^{3+} + 2\text{H}_2\text{O}$	1.999

These corrosion equations imply that an oxidizing agent, such as dissolved oxygen (D.O.) creates a strong driving force for corrosion to proceed by oxidizing elemental iron to ferrous or ferric ions.

No literature was found on the influence of D.O. on the corrosion rate of metals in the presence of phosphate compounds. Therefore, experiments were conducted to investigate the relative role of D.O. in the corrosion process in the presence of corrosion inhibitors.

In this study, D.O. concentrations were adjusted to about 4 and 8 mg/l, respectively, by bubbling nitrogen gas into University tap water to strip oxygen. Sodium-zinc phosphate (Calgon TG-10) at a dose of 0 and 20 mg/l as P_2O_5 , was added to the test water system containing the galvanic corrosion cells of cast iron and copper specimen. The experiment was continued for a seven day period.

Figures 71 and 72 present data related to the effect of D.O. and polyphosphate concentrations on the corrosion of iron. As expected, Figure 71 shows that in the system with low D.O., with or without phosphate additions, the total iron concentration found in the test water decreased initially. Figure 72 also shows that the reduction in D.O. reduced the corrosion rate of the cast iron test specimens. The addition of 20 mg/l P_2O_5 of sodium-zinc phosphate reduced the corrosion rate by 80% over the control which had no phosphate compound added at both D.O. systems. For example, in the presence of 8.0 mg/l of D.O. and a phosphate dose of 20 mg/l P_2O_5 , the corrosion rate of the iron was 26 mdd. However, in the system with high D.O. level and without the phosphate addition, the

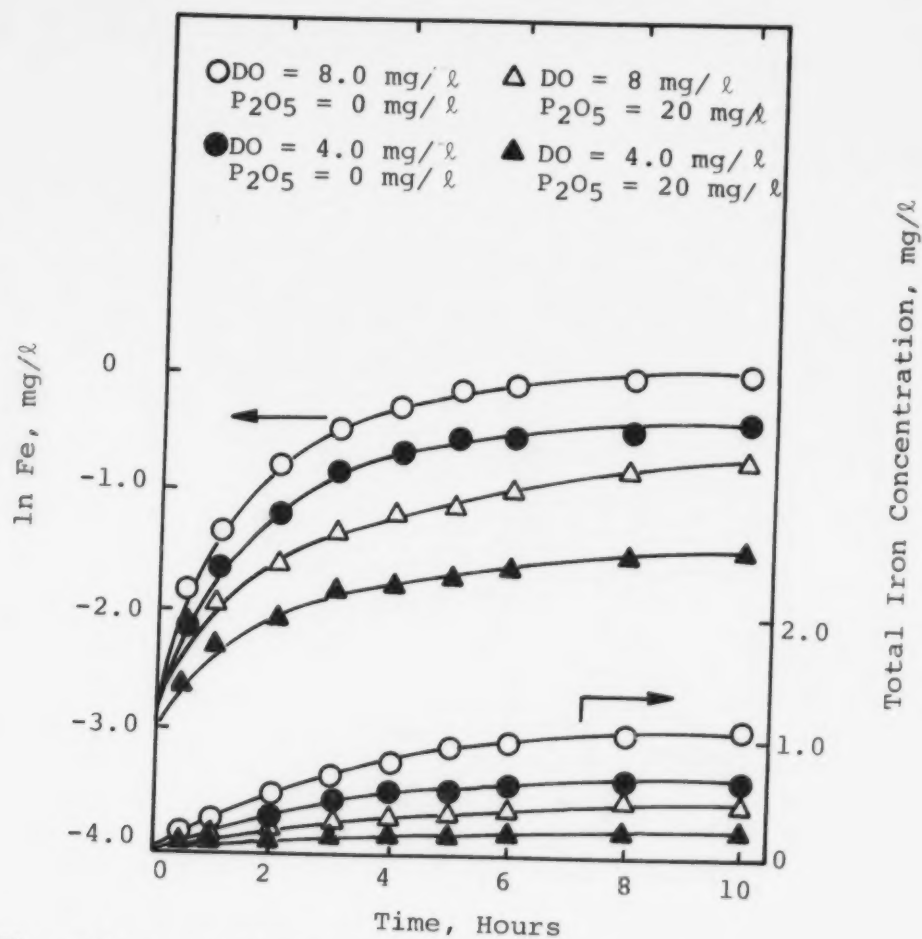


Fig. 71 Effect of Dissolved Oxygen and Sodium-Zinc Phosphate on Total Iron Concentration During Galvanic Corrosion (pH = 7.7) (Calgon TG-10)

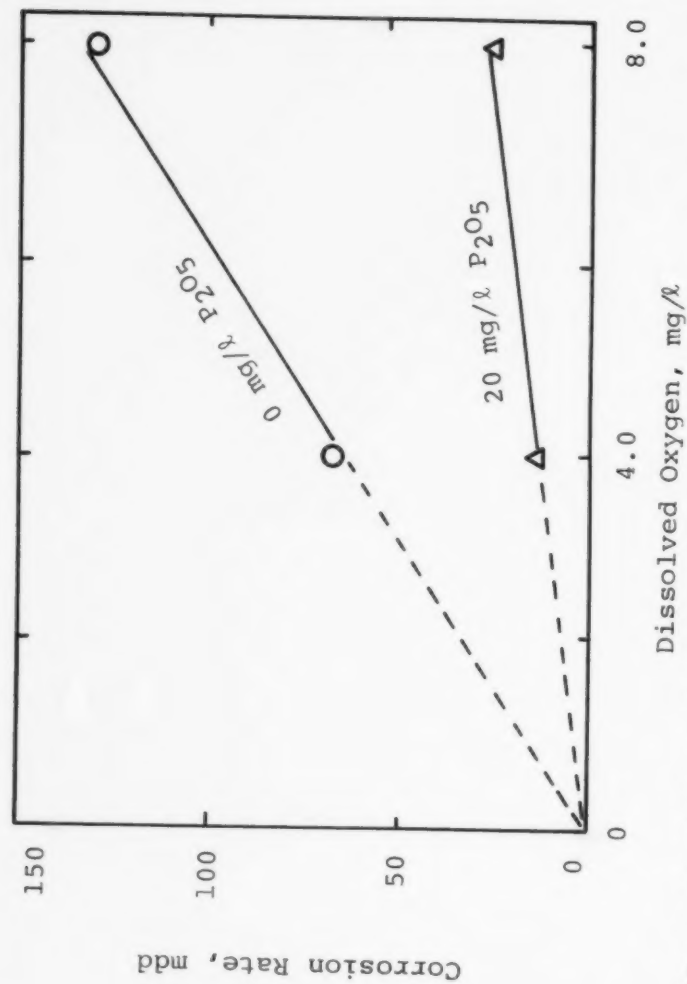


Fig. 72 Effect of Dissolved Oxygen Concentration on Corrosion of Cast Iron Test Specimens in the Presence of Sodium-Zinc Phosphate (Calgon TG-10)

corrosion rate was 131 mdd.

The cast iron test specimens generally tended to be corroded locally, except in the presence of 8 mg/l D.O. and 0 mg/l P_2O_5 where the specimen was uniformly corroded. In the presence of 20 mg/l P_2O_5 , this local corrosion of the cast iron specimens was confined to a small area.

In the case when the test water contained 4 mg/l D.O., it was evident that the copper test specimen was completely covered with a white precipitate (condensed phosphate particles) while the cast iron test specimen had localized corrosion. These observations indicate that uniform corrosion may usually be associated with water having little surface protection. On the other hand, localized corrosion may occur in an environment which offers some, but not complete, protection.

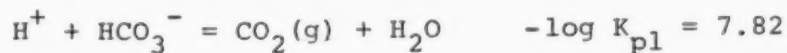
E. Chemical Water Quality Changes Due to Phosphate Additions

A series of corrosion batch tests were conducted with the selected commercial phosphate products to study water quality changes with time. Some of the chemical parameters in the test waters were found to have changed significantly due to the type and concentrations of phosphate compounds used. In order to have a better understanding of the effect of these chemical changes on corrosion control, important chemical parameters such as pH, total alkalinity, calcium, total hardness, turbidity and phosphates were analyzed separately.

(1) pH and Total Alkalinity

Figures 73 and 74 present data related to the changes in pH and total alkalinity, respectively, as a function of time in eleven sets of galvanic corrosion batch tests. The changes in pH and total alkalinity with time are plotted for the three compounds used, i.e., zinc polyphosphate, sodium hexametaphosphate and sodium metaphosphate. Figure 73 shows that the initial pH tended to increase abruptly during the first day both in the presence and absence of the phosphate compounds. After one day, the pH stabilized for the system which had no phosphate compound added. For the systems with phosphate compound additions, the pH increased by 0.3 units during the first to seventh day, ultimately stabilizing at pH 8.3.

Mixing was continuously provided throughout the experimental period. The increase in pH during the first day may be attributed to the loss of carbon dioxide according to the following chemical reaction:



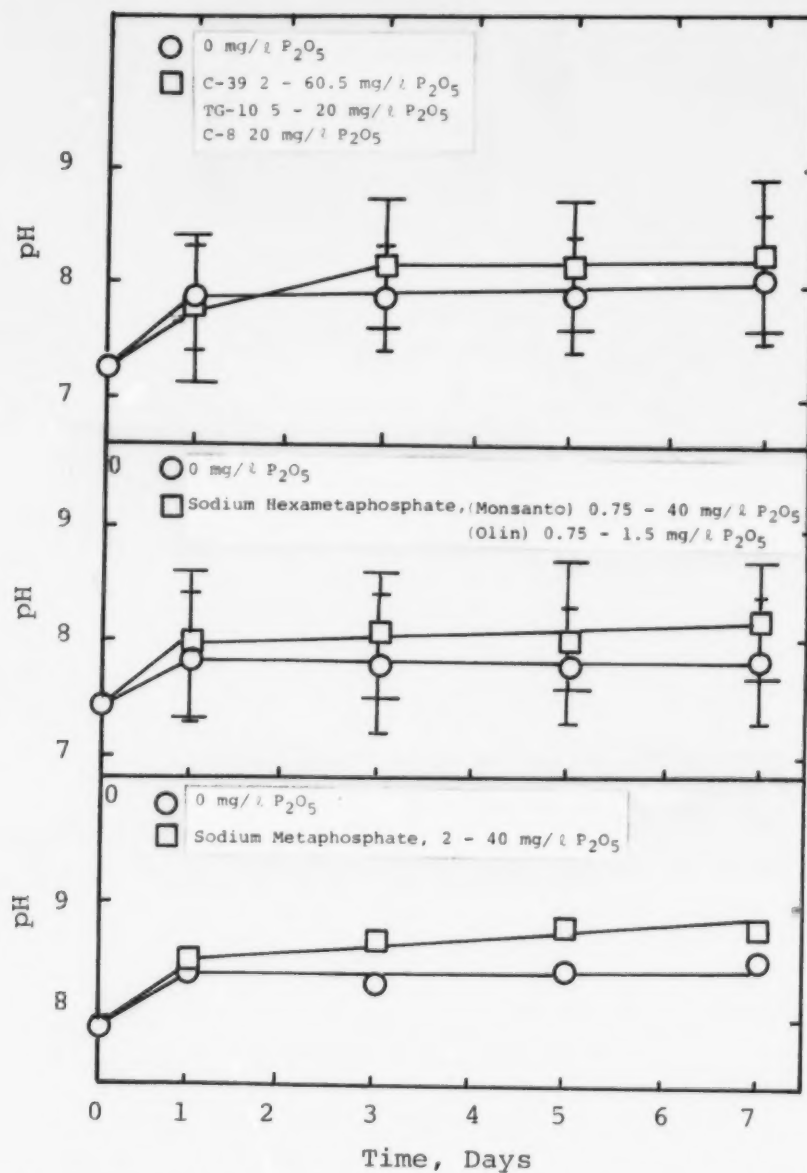


Fig. 73 Changes in pH During Galvanic Corrosion in the Presence of Phosphate Formulations

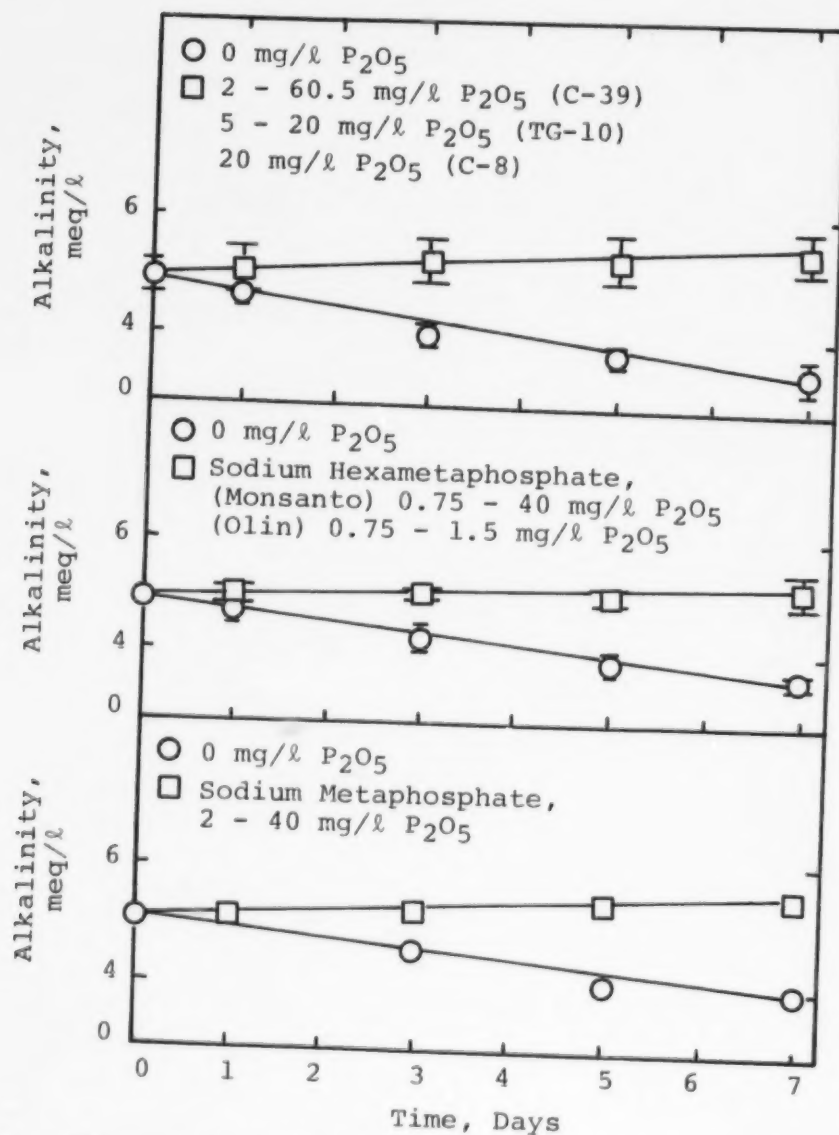
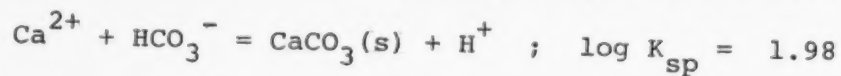


Fig. 74 Changes in Total Alkalinity During Galvanic Corrosion

Thereafter, in the system having no phosphate additions, the precipitation of calcium carbonate would stabilize the pH value due to the following chemical reaction occurring:



$$K_{\text{sp}} = \frac{[\text{Ca}^{2+}][\text{HCO}_3^-]}{[\text{H}^+]} = 10^{1.98} = 95.5$$

The pH, total alkalinity and calcium concentrations in the test waters were approximately about 7.5 mM, 2.5 mM and 1.4 mM, respectively. Using these experimental data, it was calculated that the ion product of $[\text{Ca}^{2+}][\text{CO}_3^{2-}]$ ($K=110.68$) was greater than solubility product of calcium carbonate ($K_{\text{sp}} = 95.5$). Therefore, the pH value and total alkalinity should decrease following calcium carbonate precipitation as equilibrium was approached. This explains the decrease in total alkalinity observed in Figure 74 for the control system.

On the other hand, upon the addition of phosphate, there would be no calcium carbonate precipitation owing to the complexation of calcium. Consequently, the pH value continued to increase as determined by the carbonate equilibrium, and total alkalinity did not decrease. In fact, phosphate addition even as low as 0.75 mg/l P_2O_5 , tended to increase buffering capacity of test waters. Alkalinity decreased in systems not treated with phosphate as a result of calcium carbonate precipitation as well as a result of acid produced by the hydrolysis of iron. The alkalinity remained stable in the phosphate-treated systems, increasing slightly as the condensed phosphate reverted to orthophosphate.

(2) Calcium and Total Hardness

Figures 75 and 76 present data related to the changes in calcium and total hardness as a function of time in seven sets of galvanic corrosion batch tests using University tap water. As in the previous experiment, the calcium and total hardness changes with time are plotted for the three phosphate compounds in Figure 76. In the absence of phosphate, the total hardness was observed to decrease with time following approximately zero-order reaction rate kinetics. Similar results were observed for total alkalinity decreased with time (Figure 74) confirming the precipitation of calcium carbonate in these test systems.

Under these experimental conditions, magnesium hydroxide

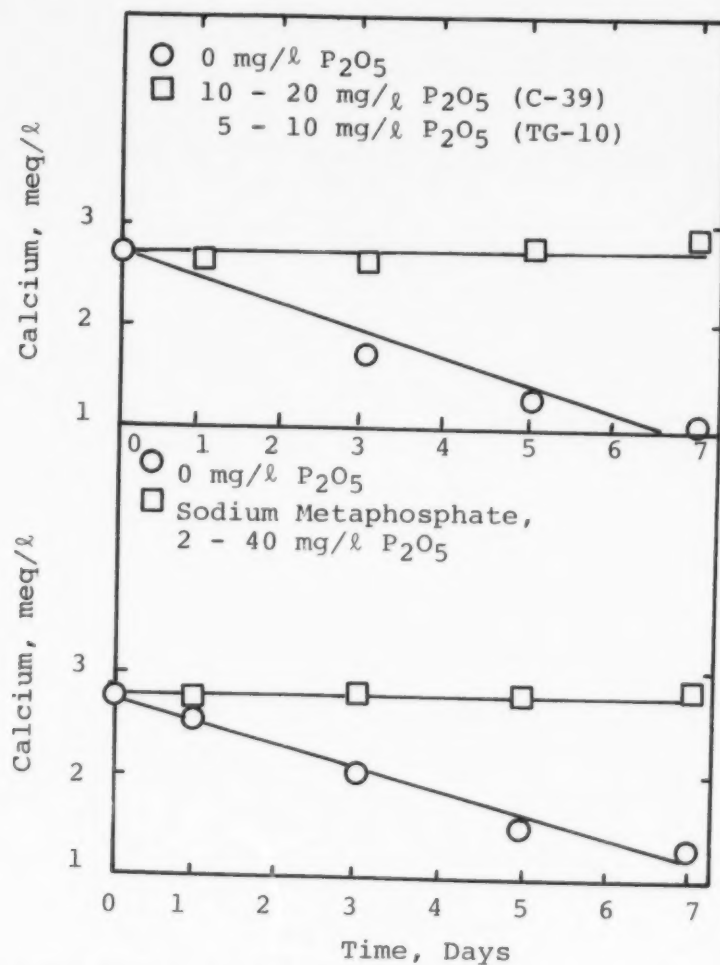


Fig. 75 Changes in Calcium Concentration as a Function of Time in the Galvanic Corrosion Batch Tests in Presence of Various Doses of Phosphate Compounds

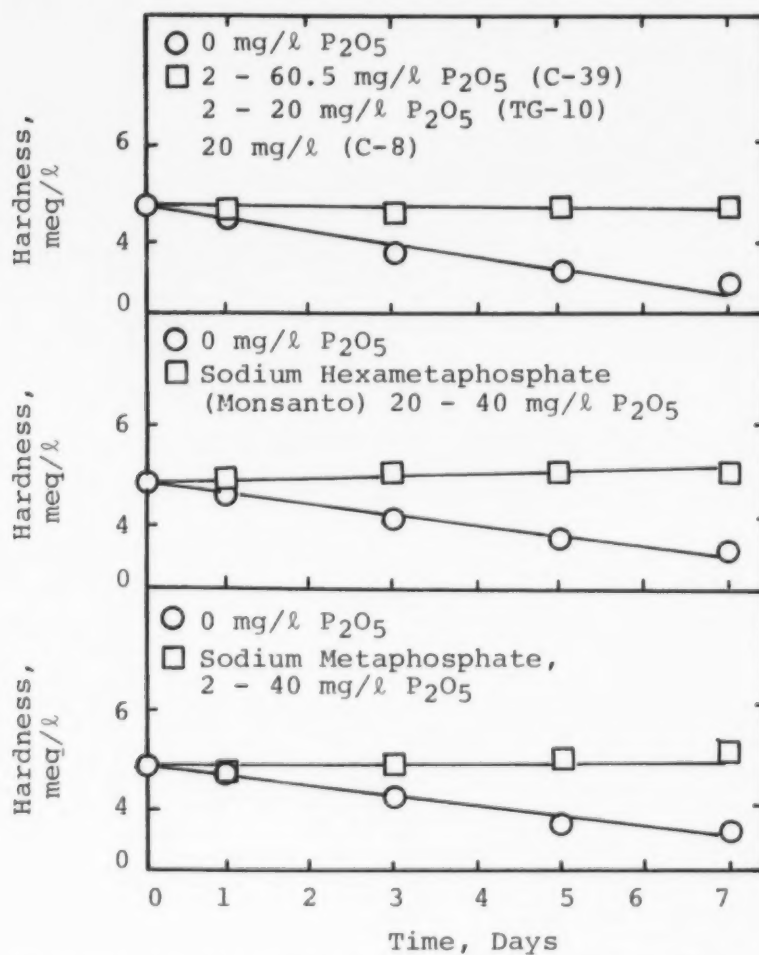
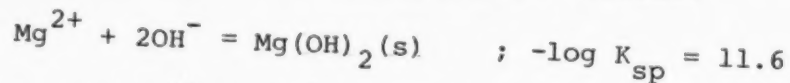


Fig. 76 Changes in Total Hardness During Galvanic Corrosion in Presence of Various Doses of Phosphate Compounds

would not be expected to precipitate. The solubility of magnesium hydroxide is calculated as follows:



$$K_{\text{sp}} = [\text{Mg}^{2+}][\text{OH}^-]^2 = 10^{-11.6}$$

The pH and magnesium hardness in the test water were approximately about 7.5 and 1mM, respectively. By substituting these values into the above equation, we get:

$$1 \times 10^{-3} \times (10^{-6.5})^2 = 10^{-16} < 10^{-11.6}$$

No precipitation should occur since the system is undersaturated with respect to $\text{Mg}(\text{OH})_2$. Only if the pH value is increased up to 10 or above, then $\text{Mg}(\text{OH})_2$ precipitation may occur:

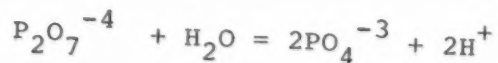
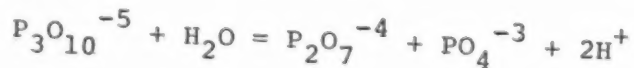
$$1 \times 10^{-3} \times (10^{-4})^2 = 10^{-11} > 10^{-11.6}$$

Experimental results which showed that magnesium hardness did not decrease in the seven-day reaction time confirmed these theoretical considerations. Magnesium concentration was calculated from the data by subtracting calcium hardness from the total hardness concentrations.

From Figures 75 and 76 it appears that the addition of either polyphosphate or metaphosphate as low as 2 mg/l P_2O_5 would generally prevent precipitation of calcium carbonate through complexation of calcium.

(3) Reversion Rate of Polyphosphate

Molecularly dehydrated polyphosphates gradually hydrolyze in aqueous solution and revert to the orthophosphate from which they were derived. For instance, hydrolysis of triphosphates and pyrophosphates occur by the following reactions:



Sawyer and McCarty (116) state that the rate of reversion is a function of temperature, pH and bacterial enzymes. In general, the reversion rate is increased by raising the temperature, lowering the pH and increasing the bacterial enzymes.

Synthetic waters were made to determine in batch systems

the effect of total alkalinity on reversion rate of polyphosphate at six different alkalinity levels, 0, 20, 70, 150, 250, and 500 mg/l as CaCO_3 . The initial phosphate (Calgon TG-10 sodium-zinc phosphate) dose was 20 mg/l P_2O_5 . Since the alkalinity will neutralize acids in the waters, it was not unexpected that the higher the alkalinity, the slower the reversion rate of polyphosphate would be. Figure 77 shows that the system with higher alkalinity tended to have more condensed phosphate remaining (upper limit) in the system. In a water of zero alkalinity, only 50% of condensed phosphate remained after seven days operation.

Synthetic waters were also made to determine in batch system the effect of calcium levels, 0, 20, 70, 130, 260, and 500 mg/l as CaCO_3 . The initial phosphate (Calgon TG-10 sodium-zinc phosphate) dose was 20 mg/l P_2O_5 . Figure 78 shows that the highest calcium concentration, 500 mg/l as CaCO_3 tended to result in the highest reversion rate of polyphosphate. Only 55% of condensed phosphate remained after seven days of test period. This might be attributed to a strong complexation reaction between high concentrations of calcium ion and orthophosphate ligand. Consequently, the hydrolytic reversion of condensed phosphate appears to be favored by increasing complexation between calcium ion and orthophosphate ligand.

F. Chemical Composition of Protective Coatings on the Cathode and Anode

As shown earlier, the phosphate addition in both batch and continuous flow corrosion test systems did not decrease the corrosion rate of cast iron specimens in the water system until a sufficient amount of phosphate (greater than 20 mg/l as P_2O_5) has been added. It was summarized that when phosphate doses are increased to 20 mg/l P_2O_5 , they may be able to form protective coatings on metal surfaces. Therefore, in this part of the study, the chemical properties of the material deposited or accumulated on metal specimens were examined so that the mechanism of corrosion inhibition by phosphate additions could be confirmed. The accumulation of material on the cathode (copper specimen) was scraped and recovered using a spatula while the material accumulated on the anode (cast iron specimen) was removed by rinsing with distilled water. The material removed from the cathode and the anode was then resuspended in 200 ml of distilled water, separately, for chemical analysis.

Two sets of specimens from batch corrosion tests using synthetic waters were utilized in this study. In the first test, the synthetic water used was the same as that described in Section B of Results and Discussions part of this chapter. Optimum sodium-zinc phosphate dosages of 20 mg/l as P_2O_5 had been added to the test water. The effect of pH on the chemical

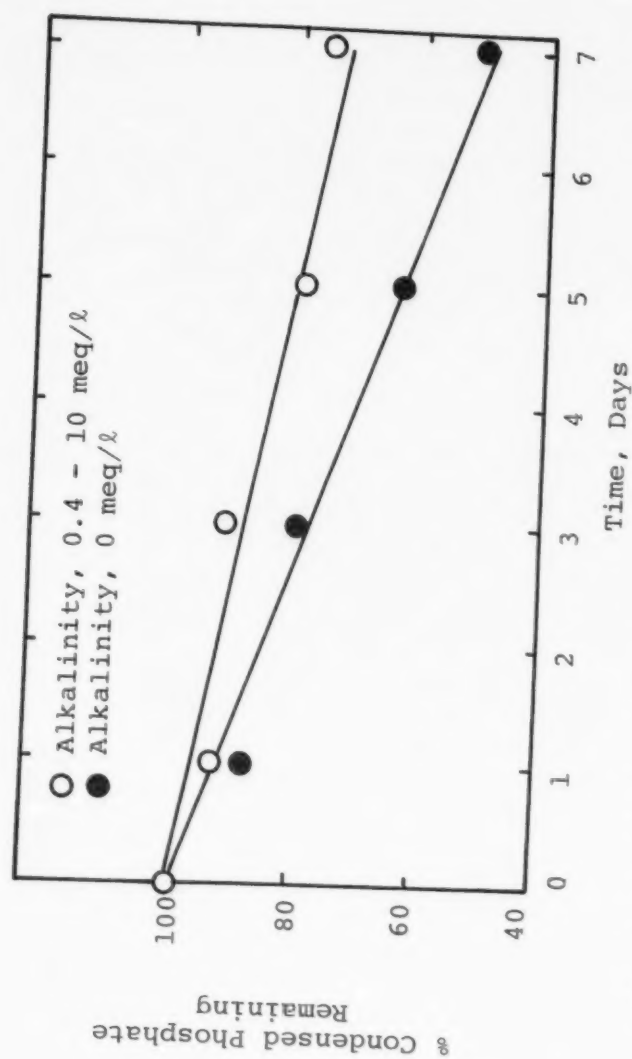


Fig. 77 Hydrolysis of Condensed Phosphate During Galvanic Corrosion
(Initial Dose of Sodium-Zinc Phosphate, 20 mg/l P_2O_5 ;
25°C; 2.26 meq/l Ca) (Calgon TG-10)

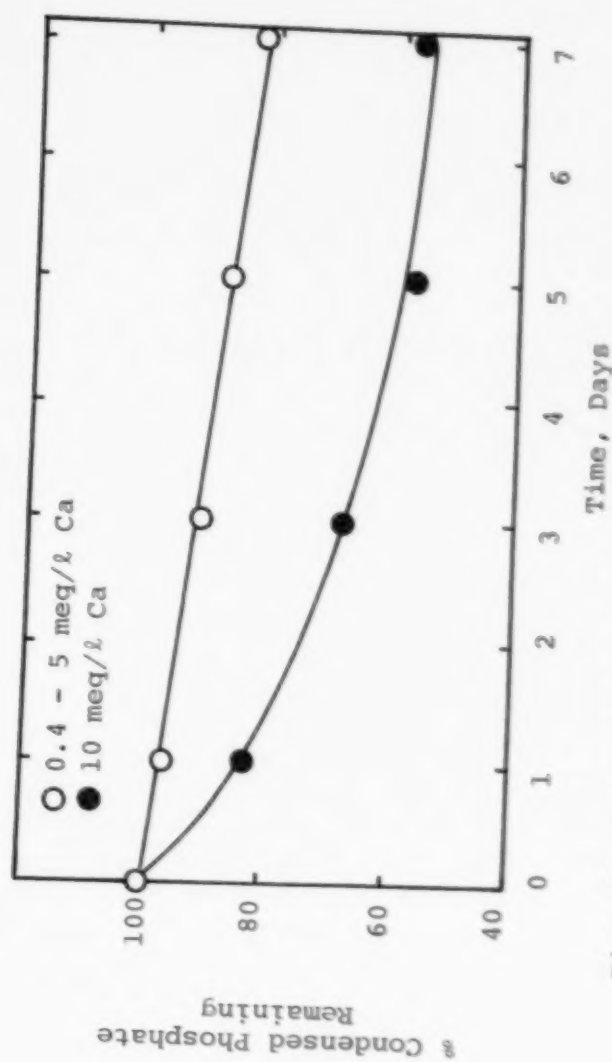


Fig. 78 Hydrolysis of Condensed Phosphate During Galvanic Corrosion (Sodium-Zinc Phosphate, 20 mg/l P_2O_5 ; 25°C; pH 8.3 - 8.8) (Calgon TG-10)

properties of the material deposited on the cathode (copper specimen) was then evaluated at six different levels of total alkalinity, 0, 20, 70, 150, 250, and 500 mg/l as CaCO_3 , respectively. Since the alkalinity of a water is a measure of its capacity to neutralize acid, the pH of these synthetic waters were found to be 6.9, 7.7, 8.2, 8.6, 8.8, and 8.9, respectively, after seven days of mixing. The results of this study are listed in Table 87.

Table 87 shows that greater amounts of total iron, calcium, total hardness (carbonate) and orthophosphate deposited and accumulated on the cathode at the lower range of values, such as 6.9 and 7.7. Stoichiometric calculations and color of the precipitate would indicate that CaCO_3 and Fe_2O_3 , respectively, had been deposited, along with some orthophosphate precipitates. However, more condensed phosphate accumulated on the cathode at high pH values, where less corrosion was observed on the cast iron anode. From the data, it appears that ferric oxides, calcium carbonate, ferric orthophosphate, calcium orthophosphate and possibly zinc orthophosphate, oxide or carbonate contributed the protective coatings at pH values between 6.9 and 8.2. On the other hand, at pH values higher than 8.2, the condensed phosphate precipitates on cathode may have been important in inhibiting corrosion.

Table 87 shows that the color of the suspensions of precipitates was linked to pH values in this study. It tended to change from yellow to white as the pH values were varied from 6.9 to 8.9.

In the second test, synthetic water was prepared, as described in Section C of Results and Discussions part of this chapter, with a sodium-zinc phosphate dose of 20 mg/l as P_2O_5 . The effect of calcium ion concentrations on the material deposited on the cathode (copper specimen) and the anode (cast iron specimen) were evaluated at six different levels of calcium ion concentrations, 0, 20, 70, 130, 260, and 500 mg/l as CaCO_3 , respectively. The results of this study are summarized in Table 88.

In general, it was found that the optimum dosage of polyphosphate (20 mg/l P_2O_5) did not significantly inhibit the corrosion rate of the metal until a sufficient amount of calcium (greater than 20 mg/l as CaCO_3) had been added. As calcium deposition increased, anodic corrosion decreased. Data from Table 88 indicate, however, that the amount of condensed phosphate compounds deposited on the cathode may be related to corrosion inhibition.

G. Corrosion Studies with the Continuous-Flow Water System

Table 87 Chemical Properties of Materials Deposited on Cathode
in Batch Systems (Calgon TG-10 Sodium-Zinc Phosphate,
20 mg/l P_2O_5)

pH	Corrosion Rate of Cast Iron mdd	Color	Total Iron $\mu\text{g/cm}^2$	Calcium $\mu\text{g as CaCO}_3$ cm^2	Total Hardness $\mu\text{g as CaCO}_3$ cm^2	Ortho- Phosphate $\mu\text{g as P}$ cm^2	Condensed Phosphate $\mu\text{g as P}$ cm^2
6.9	85.5	Yellow	78.1	42.0	63.0	32.7	0
7.7	79.4	Yellow	28.9	42.0	63.0	13.7	1.1
8.2	76.3	Yellow-White	13.1	10.5	42.0	3.4	1.9
8.6	61.3	White	5.3	5.3	10.5	1.0	2.1
8.8	61.3	White	2.6	5.3	5.3	1.1	2.1
8.9	57.1	White	3.7	10.5	42.0	1.3	5.0

Table 88 Chemical Properties of Materials Deposited on Cathode and Anode in the Batch System (Calgon TG-10 Sodium Zinc Phosphate, 20 mg/l P_2O_5)

Calcium mg/l as $CaCO_3$	Corrosion Rate mdd	Color	Total Iron $\mu g/cm^2$	Calcium μg as $CaCO_3$ $\frac{cm^2}{2}$	Total Hardness μg as $CaCO_3$ $\frac{cm^2}{2}$	Ortho- Phosphate μg as P $\frac{cm^2}{2}$	Condensed Phosphate μg as P $\frac{cm^2}{2}$
Cathode 347	0	Yellow	11.9	0	10.4	0.7	1.8
	20	Yellow	12.1	0	20.7	1.5	3.7
	70	Yellow-White	1.8	4.2	21.0	0.7	2.9
	130	White	6.5	31.3	57.4	2.9	12.4
	260	White	1.3	5.2	20.7	1.1	6.8
500		White	5.5	104.3	135.6	12.5	40.8
Anode	0	Yellow		0	15.9	4.6	29.7
20	126.8	Yellow		0	21.4	4.5	26.7
70	116.5	White		4.2	21.2	2.5	26.9
130	46.7	White		31.9	63.7	4.6	23.7
260	29.5	White		6.4	15.9	2.4	18.4
500	37.5	White		84.8	116.7	7.3	37.0
	45.3						

(1) The Effect of Various Phosphate Formulations on Corrosion

In order to determine the effect of phosphates on pipe corrosion in water distribution system, two sets of continuous flow corrosion tests were conducted with a Monsanto's sodium hexametaphosphate (SHMP), Calgon's C-39 and TG-10 zinc polyphosphate.

In the first test, the effect of adding small quantities of two commercial phosphate products, i.e., 0 mg/l P_2O_5 , 5 mg/l SHMP (3.37 mg/l P_2O_5) and 5 mg/l Calgon C-39 sodium-potassium-zinc phosphate (2.75 mg/l P_2O_5) were examined. Data related to this study are presented in Figures 79 and 80, and Table 89. From Figure 79 it can be seen that 5 mg/l of the Calgon C-39 compound inhibited corrosion of cast iron specimens, at least, during the first six hours. However, an equal amount of the SHMP did not inhibit the corrosion of the metal test specimens. Figure 80 shows the cumulative corrosion intensity (mg/cm²) changes under various test conditions. It can be seen from Figure 80 that neither C-39 nor SHMP inhibited metal corrosion over a period of 28 days in the continuous flow system. They may have, in fact, accelerated the corrosion rate of cast iron test specimens.

During the test periods, chemical analyses of the aqueous samples were performed. The results are presented in Table 89. These parameters included pH, total alkalinity, total hardness, calcium, and dissolved oxygen. Two selective corrosion indices, Langelier's saturation index (L.I.) and Ryznar's stability index (R.I.) were calculated. These parameters did not change much during the test period. From the corrosion indices, it is clear that the water of the control in this study was oversaturated with respect to calcium carbonate. Therefore, even without phosphate addition, the water would have a slight tendency to crystallize or to lay down a protective coating of solid calcium carbonate on the metal test specimens, thereby inhibiting corrosion. However, the small quantities of phosphate addition could sequester the calcium, cause the water to be undersaturated with respect to calcium carbonate, and prevent the deposition of protective coatings of calcium carbonate on the metal. As a result, the corrosion indices, such as L.I. and R.I., under these conditions cannot be relied upon to predict the tendency of phosphate-enriched water to deposit or dissolve calcium carbonate films. In other words, the equilibrium chemistry of the phosphate enriched water is greatly altered different from that of the natural water.

Having completed this initial study of the effect of small quantities of phosphates, additional efforts were made to examine the higher concentrations of the zinc-bearing corrosion

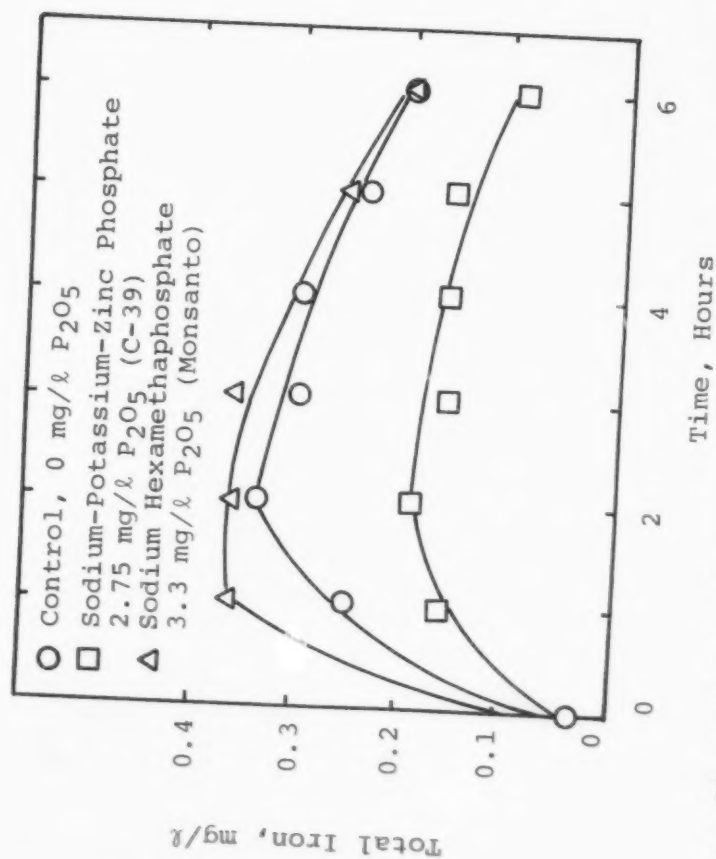


Fig. 79 Total Iron During Continuous-Flow Corrosion Testing in the Presence of Various Phosphate Formulations

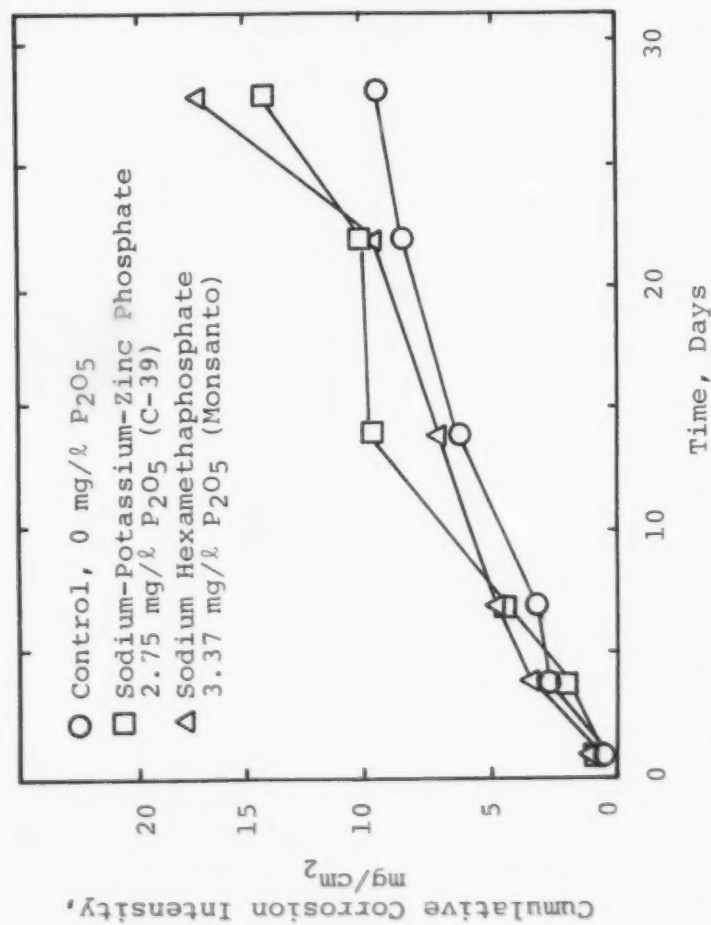


Fig. 80 Cumulative Corrosion Intensity of Cast Iron During Continuous-Flow Corrosion Testing in Presence of Various Phosphate Compounds

Table 89 Results of Chemical Analysis of Water in Continuous-Flow Corrosion Test System

Test Condition	Time (days)	Temp (°C)	pH	*pHs	Total Alkalinity (mg/l as CaCO ₃)	Total Hardness (mg/l as CaCO ₃)	Calcium (mg/l as CaCO ₃)	D.O. (mg/l)	*L.I.	*R.I.
Tap Water	1	24.0	7.8	7.4	251	240	137	8.55	0.4	7.0
	4	23.5	7.8	7.5	248	240	137	8.80	0.3	7.2
	7	23.0	7.7	7.5	245	240	137	9.00	0.2	7.3
	14	23.0	7.8	7.5	246	240	137	8.90	0.3	7.2
	28	22.0	7.7	7.4	247	245	142	8.50	0.3	7.1
Control	1	24.0	7.8	7.5	245	240	137	8.15	0.3	7.2
	4	23.5	7.8	7.5	248	240	137	8.20	0.3	7.2
	7	23.0	7.7	7.5	243	240	137	8.20	0.2	7.3
	14	23.0	7.8	7.5	244	242	139	8.30	0.3	7.2
	28	22.0	7.7	7.4	247	246	143	8.20	0.3	7.1
G-39 (2.75 mg/l as P ₂ O ₅)	1	24.0	7.8	7.5	248	238	135	8.10	0.3	7.2
	4	23.5	7.8	7.5	248	238	135	8.10	0.3	7.2
	7	23.0	7.7	7.5	244	240	137	8.30	0.2	7.3
	14	23.0	7.8	7.5	247	242	139	8.30	0.3	7.2
	28	22.0	7.8	7.4	248	246	143	8.15	0.4	7.0
Monanto (3.37 mg/l as P ₂ O ₅)	1	24.0	7.8	7.5	247	238	135	8.00	0.3	7.2
	4	23.5	7.8	7.5	247	238	135	8.00	0.3	7.2
	7	23.0	7.7	7.5	245	240	137	8.30	0.2	7.3
	14	23.0	7.8	7.4	245	244	141	8.35	0.4	7.0
	28	22.0	7.8	7.4	245	244	141	8.15	0.4	7.0

* pHs = pH at which a given water is in equilibrium with solid calcium carbonate

* L.I. = Langelier's Saturation Index

* R.I. = Ryznar's Stability Index

inhibitor, Calgon TG-10. Figures 81 and 82, and Table 90 present data related to this study. Figure 81 shows that the sodium-zinc phosphate formulation, at doses of 10 and 20 mg/l as P_2O_5 , inhibited corrosion of cast iron specimens during the first six hours. Figure 81 also shows slightly increased turbidity in phosphate-enriched water.

Figure 82 shows the cumulative corrosion intensity (mg/cm^2) changes under various test conditions. Only the 20 mg/l P_2O_5 doses decreased metal corrosion rate, the increase was about 56% at 28 days of exposure in the continuous flow system. A dosage of 10 mg/l P_2O_5 produced no corrosion inhibition, and may have, in fact, increased the corrosion rate by about 14%. Generally, the results of chemical analysis in Table 90 are initially similar to those obtained from the previous study and did not change much during the test period.

These results imply that the use of small quantities of commercial phosphate products may enhance the corrosion of cast iron pipes in water distribution systems. Only a phosphate addition of 20 mg/l P_2O_5 or greater results in the formation of protective coatings on the metal surfaces in the laboratory continuous flow water system.

(2) Microbiological Growth Induced by Phosphate Additions

It is possible that phosphate additions contribute to quality deterioration by serving as an essential nutrient for microbiological growth. In order to determine the effect of phosphates on microbiological potential in water distribution systems, two sets of continuous-flow water tests using University tap water were conducted with three different commercial phosphate products, i.e., Monsanto's sodium hexametaphosphate, Calgon's C-39 sodium-potassium-zinc glassy phosphate and TG-10 sodium-zinc phosphate glasses. Standard plate counts were measured and taken as an indicator of microbiological growth in these experiments.

Table 91 shows that, by the addition of 5 mg/l of sodium-potassium-zinc glassy phosphate (2.7 mg/l as P_2O_5) and 5 mg/l of sodium hexametaphosphate (3.37 mg/l as P_2O_5), standard plate counts increased up to 30 times (35°C, 2 day incubation time) as much as the control during 1.5 hours of detention in the continuous-flow water systems. However, there was no major difference in reduction of dissolved oxygen. Similar results are shown in Table 92 where, by the addition of 18 mg/l and 36 mg/l sodium-zinc phosphate glasses (10 and 20 mg/l as P_2O_5 , respectively), standard plate counts increased by a factor of 80 larger. There was also a somewhat dissolved oxygen reduction in the phosphate-enriched systems. As a result, in practice, higher chlorine residuals may be needed to control additional microbiological growth caused by phosphate additions

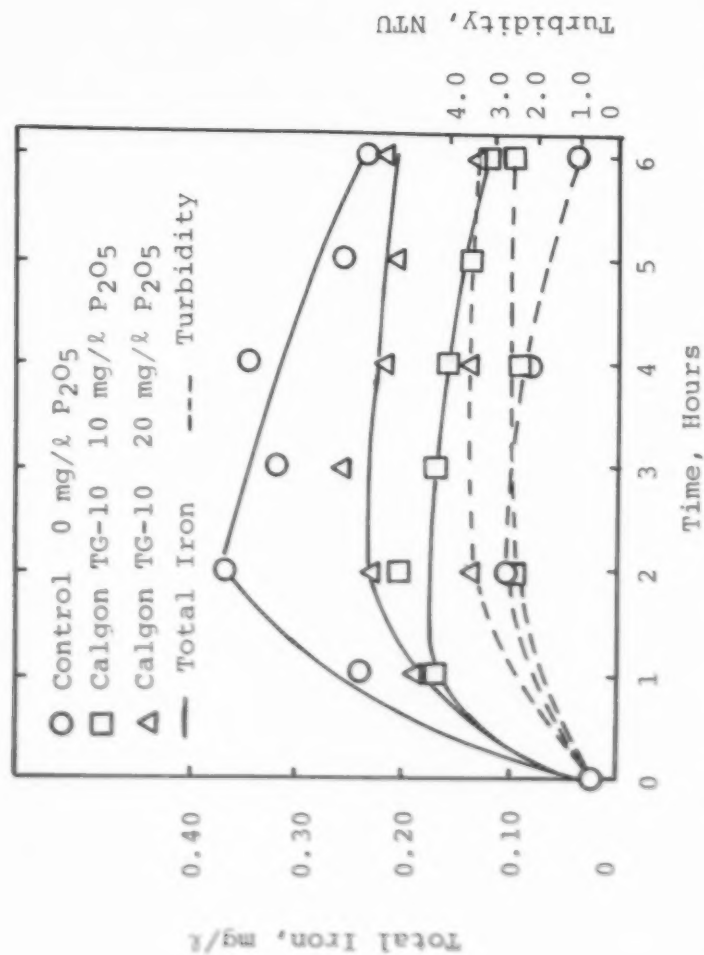


Fig. 81 Total Iron and Turbidity During Continuous-Flow Corrosion Testing in Presence of Various Phosphate Compounds

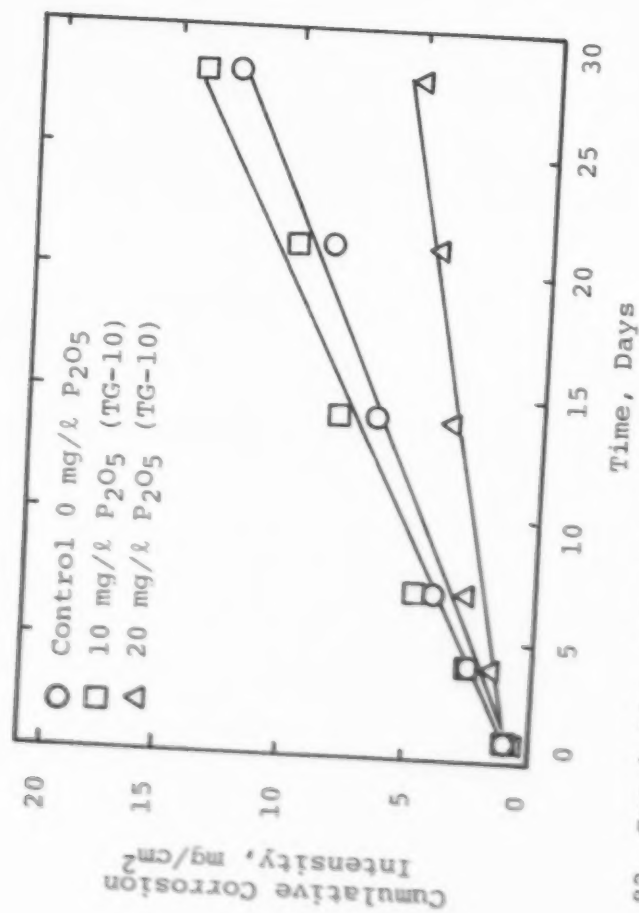


Fig. 82 Cumulative Corrosion Intensity of Cast Iron Specimens During Continuous-Flow Corrosion Testing in Presence of Various Doses of Sodium-Zinc Phosphate

Table 90 Results of Chemical Analysis of Water in Continuous-Flow Corrosion Test System

Test Condition	Time (days)	Temp. (°C)	pH	*pHs	Total Alkalinity (mg/l as CaCO ₃)	Total Hardness (mg/l as CaCO ₃)	Calcium (mg/l as CaCO ₃)	D.O. (mg/l)	*L.I.	*R.I.
Tap Water	1	26.0	7.8	7.5	249	238	133	8.70	0.3	7.2
	4	24.0	7.9	7.5	247	238	135	9.15	0.4	7.1
	7	26.0	7.9	7.5	245	238	135	8.95	0.4	7.1
	14	22.0	7.9	7.5	246	236	139	9.45	0.4	7.1
	28	23.0	7.9	7.5	251	240	134	9.00	0.4	7.1
Control	1	26.0	7.8	7.5	248	237	134	8.45	0.3	7.2
	4	24.0	7.9	7.5	248	238	136	8.60	0.4	7.1
	7	26.0	7.9	7.5	246	237	135	8.55	0.4	7.1
	14	22.0	8.0	7.4	253	240	139	9.00	0.6	6.8
	28	23.0	7.9	7.5	253	239	134	8.65	0.4	7.1
TCL-10 (10 mg/l as P ₂ O ₅)	1	26.0	7.8	7.5	248	238	135	8.50	0.3	7.2
	4	24.0	7.9	7.4	251	238	138	8.70	0.5	6.9
	7	26.0	7.8	7.5	248	239	137	8.50	0.3	7.2
	14	22.0	7.9	7.4	256	239	138	8.90	0.5	6.9
	28	23.0	7.9	7.4	256	238	138	8.70	0.5	6.9
TCL-10 (20 mg/l as P ₂ O ₅)	1	26.0	7.8	7.4	260	237	134	8.40	0.4	7.0
	4	24.0	7.8	7.4	262	237	133	8.60	0.4	7.0
	7	26.0	7.8	7.4	262	238	134	8.50	0.4	7.0
	14	22.0	7.8	7.4	277	234	125	8.50	0.4	7.0
	28	23.0	7.9	7.4	269	234	133	8.45	0.5	6.9

* pHs = pH at which a given water is in equilibrium with solid calcium carbonate

* L.I. = Langelier's Saturation Index

* R.I. = Ryznar's Stability Index

Table 91 Bacterial Growth in Continuous-Flow Corrosion Test System in Presence of Calgon C-39 and Monsanto's Sodium Hexamethaphosphate (SHMP) (Detention Time - 1.5 hours)

Time (days)	Temp (°C)	Tap H ₂ O ^o SPC** (no./ml)	Control DO Reduction (mg/l)	C-39 2.75 SPC** (no./ml)	mg/l as P ₂ O ₅ DO Reduction (mg/l)	SHMP 3.37 SPC** (no./ml)	mg/l as P ₂ O ₅ DO Reduction (mg/l)
1	24.0	5.5x10 ³	7.5x10 ³	0.40	0.45	2.6x10 ⁴	0.50
4	23.3	2.5x10 ³	1.2x10 ⁴	0.50	0.50	2.8x10 ⁵	0.70
7	23.0	1.4x10 ³	6.0x10 ⁴	0.70	0.60	9.0x10 ⁴	0.60
14	23.0	7.1x10 ³	4.4x10 ⁴	0.50	0.50	4.0x10 ⁴	0.40
22	32.0	1.3x10 ³	1.3x10 ⁵	1.20	1.05	4.8x10 ⁴	1.00
28	22.0	2.7x10 ³	4.3x10 ⁴	0.30	0.30	1.7x10 ⁴	0.35

* Influent Water

** Loop Effluent Water

Table #2 Bacterial Growth in Continuous-Flow Corrosion Test System in Presence of Calgon FG-10 (Sodium-Zinc Phosphate) (Detention Time = 1.5 hours.

Flow Temp (days) (°C)	Tap H ₂ O SPC** (no./ml)	SPC** (no./ml)	Control NO Reduction (mg/l)	10 mg/l SPC** (no./ml)	as P ₂ O ₅ NO ₂ Reduction (mg/l)	20 mg/l SPC** (no./ml)	as P ₂ O ₅ NO ₂ Reduction (mg/l)
1 26.0	5.8x10 ²	8.2x10 ²	0.20	9.1x10 ²	0.10	1.1x10 ³	0.20
4 26.0	5.2x10 ²	1.1x10 ³	0.35	6.7x10 ³	0.40	7.1x10 ³	0.50
7 26.0	5.8x10 ²	1.0x10 ⁴	0.35	2.9x10 ⁴	0.35	5.2x10 ⁵	0.45
14 22.0	8.9x10 ²	3.3x10 ⁶	0.20	1.1x10 ⁵	0.50	8.8x10 ⁵	0.75
21 21.0	5.5x10 ²	8.7x10 ³	0.30	1.6x10 ⁴	0.30	7.0x10 ⁵	0.65
28 23.0	7.6x10 ²	3.5x10 ³	0.30	9.9x10 ³	0.25	4.5x10 ⁴	0.50

* Influent Water

** Loop Effluent Water

to water distribution systems.

H. Particles Formation Studies in Batch Systems

To better understand the characteristics of protective coatings formed during treatment with phosphates, the role of phosphate dosages, calcium concentration and total alkalinity in affecting the particle were investigated. Sodium-zinc phosphate glasses (Calgon TG-10) was chosen for this study. Particle size distribution was determined by HIAC particle counter.

(1) Effect of Various Phosphate Doses on Particle Formation

Table 93 and Figures 83 through 85 show the results of studies related to the effects of various phosphate dosages on particle formation. Figure 83 shows that increasing the amount of sodium-zinc phosphate glasses from 2 to 40 mg/l as P_2O_5 tended to increase both total particle numbers and turbidity in the 10 minutes mixing time. Figures 84 and 85 show the particle size distribution of University tap water and phosphate-enriched tap water, respectively. For the University tap water, the ion product of calcium carbonate ($K = 110.68$) was greater than solubility product of calcium carbonate ($K_{sp} = 95.5$) indication the tap water is supersaturated with respect to $CaCO_3$. Therefore, in Figure 84, most particles could be contributed by calcium carbonate precipitates. On the other hand, in Figure 85, most particles could be contributed by various forms of calcium phosphate precipitates. In both cases, about 55% - 60% of particles were found in the 5 - 10 micron range of particle size.

If we assume that these colloidal precipitates were the result of nucleation, then they would offer available sites for rapid subsequent crystal growth and not be limited until chemical equilibrium is reached.

(2) Effects of Various Calcium Concentrations on Particle Formation

Synthetic waters were made from distilled water for this study as following:

Table 93

Particle Formation as a Function of Sodium-Zinc Phosphate Dosage in Batch Systems (Calgon TG-1, University Tap Water, 25°C, pH = 8.0, Alkalinity = 254 mg/l as CaCO₃, Ca = 135 mg/l as CaCO₃, Reaction Time = 10 minutes)

Particles #/20 ml Particle Size Microns	mg/l P ₂ O ₅ Doses				
	0	2	5	10	20
5 - 10	1171	1251	1600	1739	1993
10 - 15	315	538	549	677	876
15 - 20	171	379	285	377	636
20 - 25	77	159	80	138	216
25 - 30	28	103	37	67	123
30 - 35	17	47	31	36	60
35 - 40	8	21	11	27	36
40 - 45	7	23	12	18	41
45 - 50	4	20	3	12	21
50 - 75	12	34	4	23	29
75 - 100	3	5	5	4	6
100 - 300	2	2	0	4	5
Total Number	1815	2582	2617	3122	4042
Turbidity NTU	0.20	0.21	0.18	0.22	0.30
					0.53
					6350

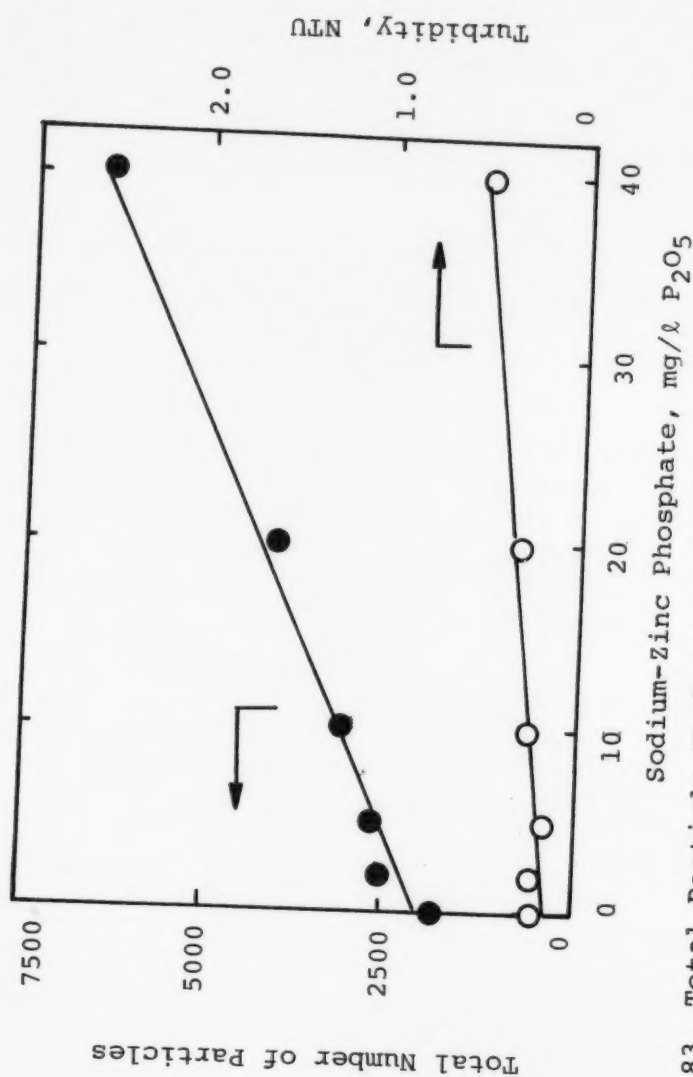


Fig. 83 Total Particle Number and Turbidity as a Function of Sodium-Zinc Phosphate Dosage (University Tap Water, 25°C, pH = 9.0, Alkalinity = 5 meq/l; Ca^{2+} = 2.7 meq/l; Reaction Time = 10 minutes.)

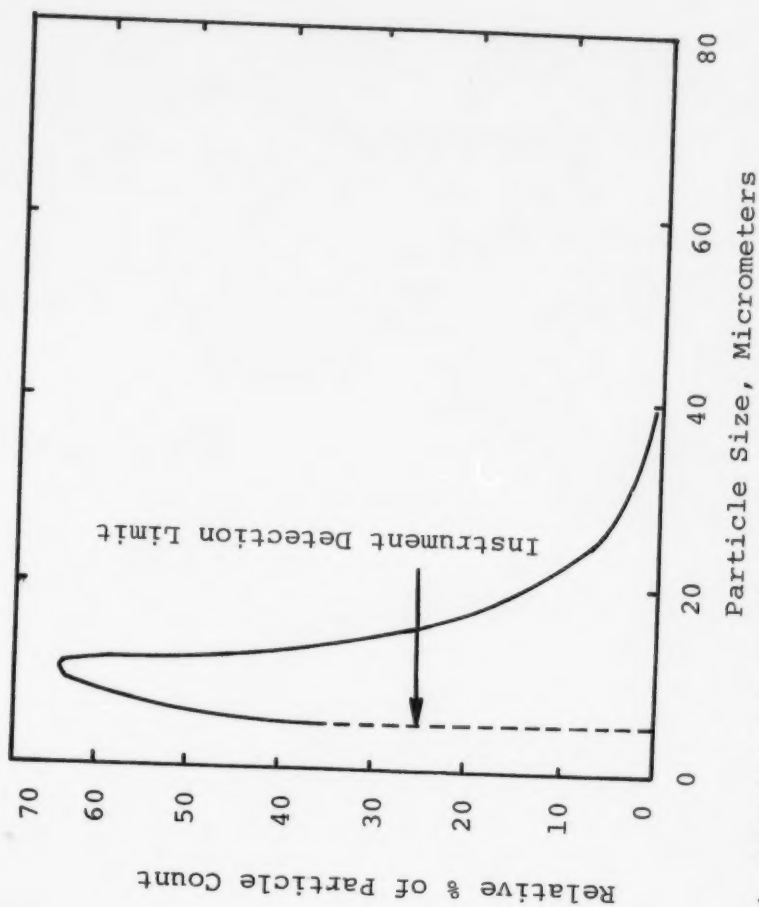


Fig. 84 Particle Size Distribution (University Laboratory Tap Water, 25°C; pH = 8.0; Alkalinity = 5 meq/l; Ca^{2+} = 2.7 meq/l; Reaction Time = 10 minutes)

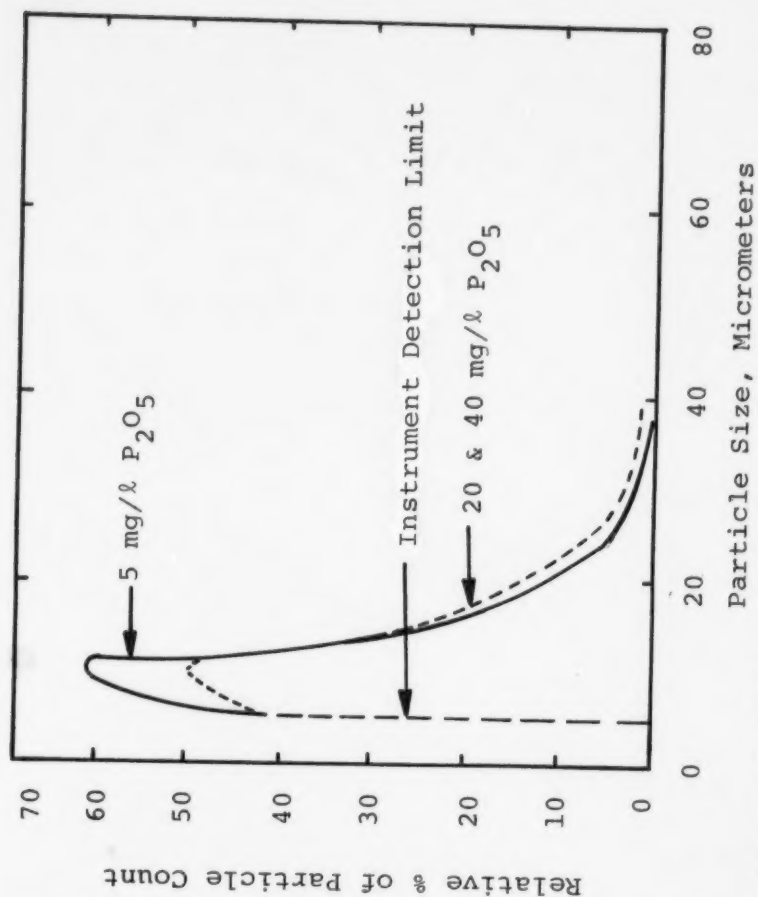


Fig. 85 Effect of Sodium-Zinc Phosphate Addition on Particle Size Distribution (25°C; pH = 8.0; Alkalinity = 5 meq/l; Ca^{2+} = 2.7 meq/l; Reaction Time = 10 minutes)

Synthetic Water Composition:

Chemical	Concentration (mg/l)	Ion Concentration (mg/l)		
		Na ⁺	Alakalinity	P ₂ O ₅
NaHCO ₃	218	60	130	
Calgon TG-10	36.36			20

Alkalinity expressed as mg/l CaCO₃.

The effect of calcium concentration on particle formation was evaluated at six different concentrations, 0, 20, 70, 130, 260, and 500 mg/l as CaCO₃. The results in Table 94, Figures 86 and 87 of this study are presented. As expected, increasing calcium concentrations tended to increase both total particles and turbidity within the 10 minutes mixing time. Figure 87 shows that the addition of calcium tended to shift the particle distribution curve to the right, i.e., increasing the formation of larger sized particles, presumably as calcium carbonate and phosphate precipitates. Again, more than 50% of particles were found in the range of particle size 5 - 10 micron.

(3) Effects of Total Alkalinity on Particle Formation

Synthetic waters were made from distilled water for this study as following:

Synthetic Water Composition:

Chemical	Concentration (mg/l)	Ion Concentration (mg/l)		
		Ca ²⁺	Cl ⁻	P ₂ O ₅
CaCl ₂ · 2H ₂ O	190.78	130	92	
Calgon TG-10	36.36			20

Calcium ion expressed as mg/l CaCO₃.

The effect of total alkalinity on particle formation were then evaluated at six different concentrations, 0, 20, 70, 150, 250, 500 mg/l as CaCO₃. The results of this study are presented in Table 95, Figures 88 and 89. Figure 88 shows that increasing total alkalinity tended to increase turbidity. However, the total number of particles initially increased

Table 94 Particle Formation as a Function of Calcium Concentration in Batch System (Synthetic Water, 25°C, pH = 7.0, Alkalinity = 130 mg/l as CaCO₃, Calgon TG-10, 20 mg/l as P₂O₅, Reaction Time = 10 minutes)

Particles #/20 ml Particle Size Microns	0	Calcium Concentration, mg/l as CaCO ₃		
		20	70	130
5 - 10	2305	1205	2324	3190
10 - 15	583	401	792	1248
15 - 20	198	196	381	762
20 - 25	79	81	171	282
25 - 30	54	47	124	210
30 - 35	33	36	73	126
35 - 40	18	6	33	58
40 - 45	20	14	67	78
45 - 50	17	9	46	60
50 - 75	34	14	56	78
75 - 100	2	3	25	4
100-300	2	7	10	4
Total Number	3345	2019	4102	6100
Turbidity NTU	0.24	0.22	0.22	0.23
				0.87
				2.5
				27304
				16375
				8484
				3884
				1754
				736
				534
				324
				158
				176
				106
				176
				40
				36
				0

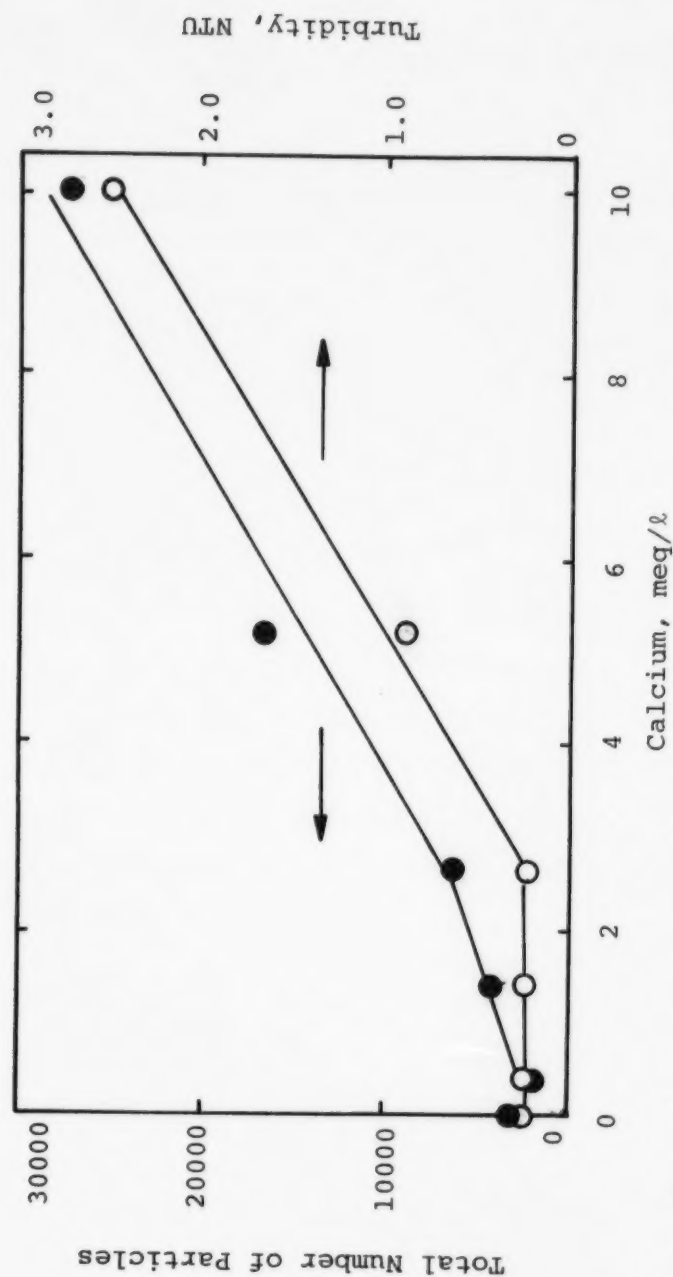


Fig. 86 Effect of Calcium Ion Concentration on Total Particle Number and Turbidity (25°C, pH = 7.0, Alkalinity = 2.6 meq/l; Calgon TG-10, 20 mg/l P_2O_5 ; Reaction Time = 10 minutes)

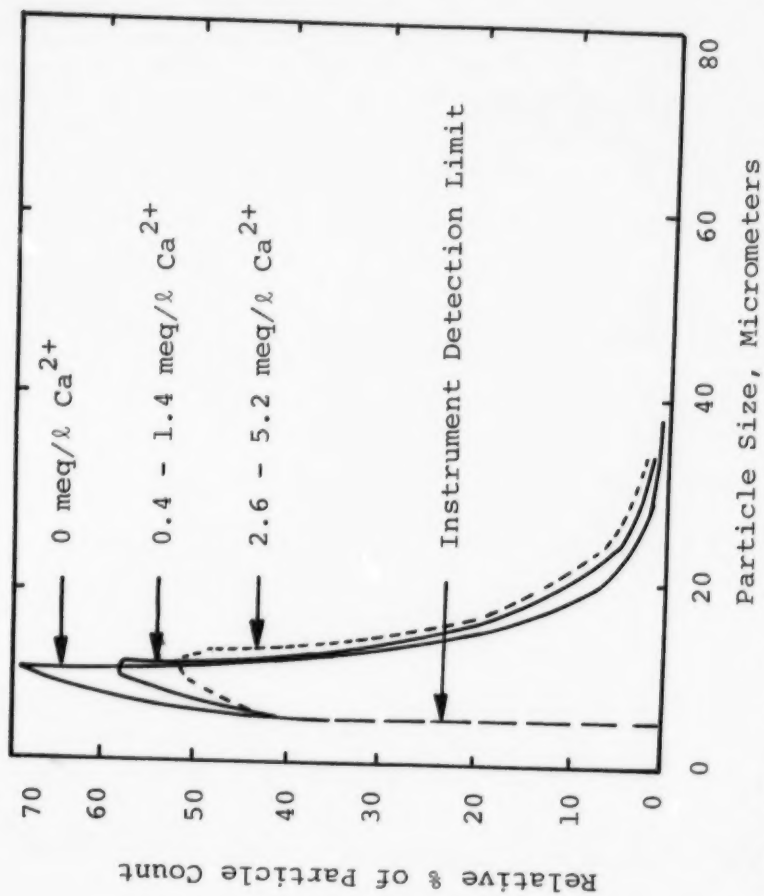


Fig. 87 Effect of Calcium Concentration on Particle Size Distribution
(25°C; pH = 7.0; Alkalinity = 2.6 meq/l; Calgon TG-10,
20 mg/l P_2O_5 ; Reaction Time = 10 minutes)

Table 95 Particle Formation as a Function of Total Alkalinity in Batch Systems (Synthetic Water, 25°C, $\text{Ca}^{++} = 130 \text{ mg/l}$ as CaCO_3 , Calgon TG-10, 20 mg/l as P_2O_5 , Reaction Time = 10 minutes)

Particles #/20 ml Particle Size Microns	0	Total Alkalinity, mg/l as CaCO_3			
		20	70	150	250
5 - 10	988	8284	5083	3928	1868
10 - 15	316	1722	919	1280	478
15 - 20	160	503	356	516	225
20 - 25	60	162	113	164	72
25 - 30	36	97	88	97	44
30 - 35	21	67	34	51	25
35 - 40	7	25	9	23	4
40 - 45	9	23	35	21	14
45 - 50	3	7	17	17	10
50 - 75	6	32	24	28	20
75 - 100	3	7	8	6	7
100-300	0	2	3	3	3
Total Number	1609	10931	6689	6134	2770
Turbidity NTU	0.12	0.20	0.24	0.59	1.1
					3.8
					4513

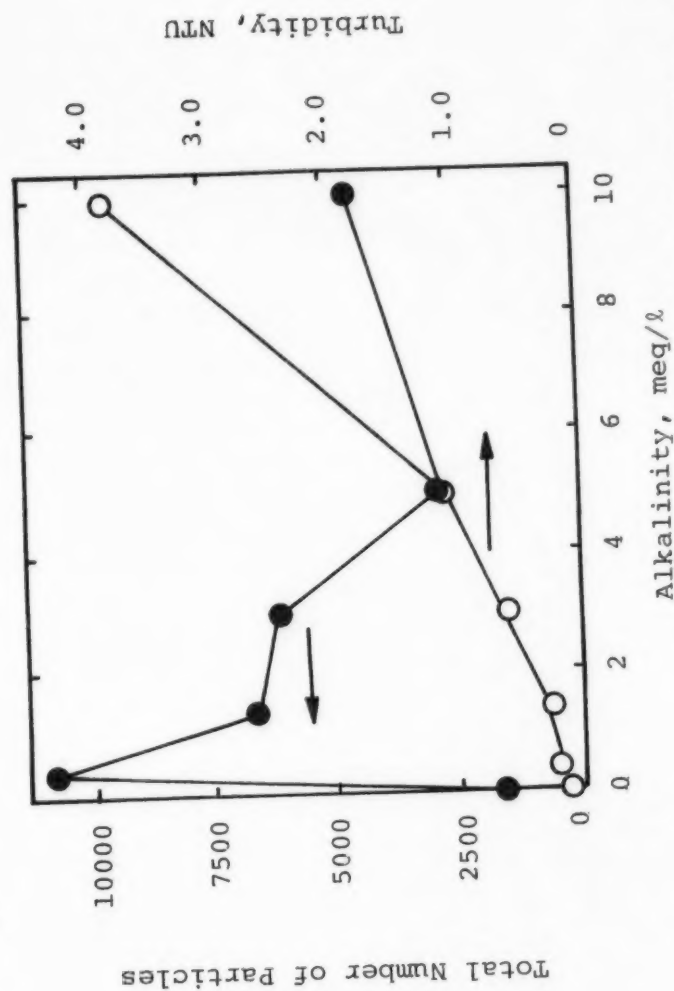


Fig. 88 Effect of Alkalinity on Total Particle Numbers and Turbidity
(25°C; Ca^{2+} = 2.6 meq/l; Calgon TG-10, 20 mg/l P_2O_5 ;
Reaction Time = 10 minutes)

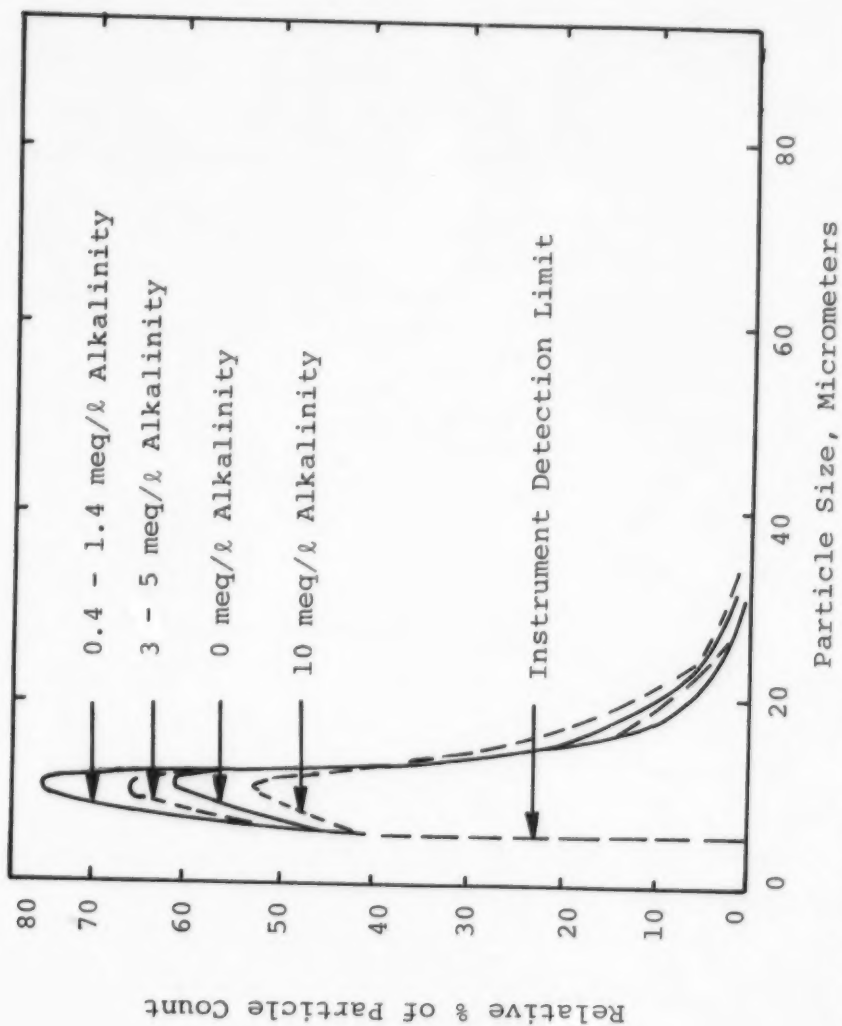


Fig. 89 Effect of Alkalinity on Particle Size Distribution (25°C;
 $\text{Ca}^{2+} = 2.6 \text{ meq/l}$; Calgon TG-10, 20 mg/l P_2O_5 ; Reaction
 Time = 10 minutes)

significantly, then declined with the further increase in alkalinity. Again, more than 50% of the particles found were in the colloidal size range (5 - 10 micron).

Overall, the number of particles present in all the samples studied were very low and observed differences may not be as significant as the relative numbers indicate.

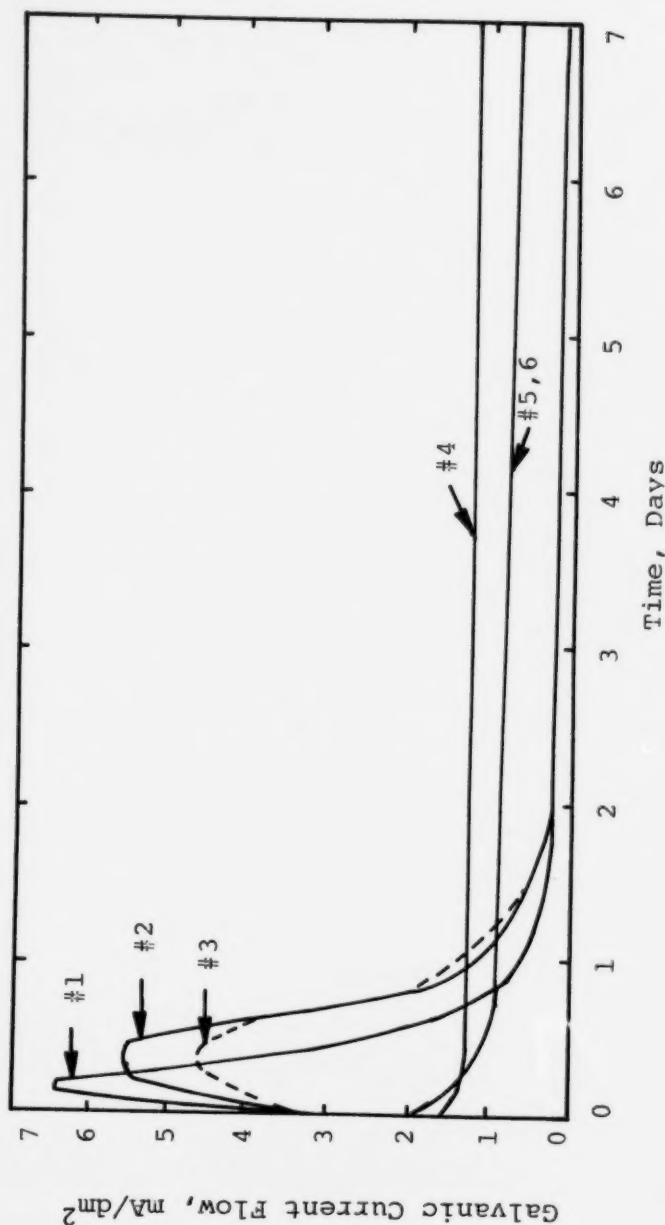
I. Galvanic Current Studies

Two galvanic cell current measurement studies were conducted in batch systems using University laboratory tap water.

In the first test, the effect of sodium-zinc phosphate glasses dosage of 0 and 20 mg/l P_2O_5 on galvanic current flow and corrosion rate at three cell spacings (distance between cast iron and copper specimens were 1/2", 3 and 6" apart, respectively) was conducted. This test was conducted to determine how the spacing of the specimen may affect its corrosion behavior. Figure 90 shows that in the absence of phosphate, the decreasing spacings of galvanic cells resulted in increased galvanic current in the first five hours. Later, the current became stable through the seven-day test period. Figure 90 shows that the addition of 20 mg/l as P_2O_5 of 1/2" cell spacings results in slightly higher galvanic currents at steady state.

In the second test, the effect of adding sodium-zinc phosphate glasses on the galvanic current flow and corrosion rate were evaluated at six different concentrations: 0, 2, 5, 10, 20, and 40 mg/l as P_2O_5 . Figure 91 shows the galvanic current flow of the corrosion cells versus time. The sodium-zinc phosphate glasses at dosages of 2 - 10 mg/l P_2O_5 were found to be corrosive (high corrosion rate) and tended to be accompanied by increased galvanic currents through the seven-day test periods. On the other hand, dosage of 20 - 40 mg/l as P_2O_5 were found to diminish corrosion and depress the galvanic current.

The University tap water is supersaturated with respect to calcium carbonate. It is important to conduct further experiment to investigate the effect of phosphate dosage on galvanic current flow and corrosion rate in test systems of unsaturated state of calcium carbonate. Therefore, synthetic waters were made from distilled water as shown below:



Test Number	Sodium-Zinc Phosphate, mg/l P_2O_5	Corrosion Cell Spacings (mm)	Corrosion Rate, $mg/dm^2/day$
1	0	13	138.56
2	0	75	150.29
3	0	150	143.42
4	20	13	69.99
5	20	75	60.90
6	20	150	70.94

Fig. 90 Effect of Galvanic Corrosion Cell Spacings on Current Flow and Corrosion Rates in Batch Systems in Presence of Sodium-Zinc Phosphate (25°C; University Laboratory Tap Water) (Calgon TG-10)

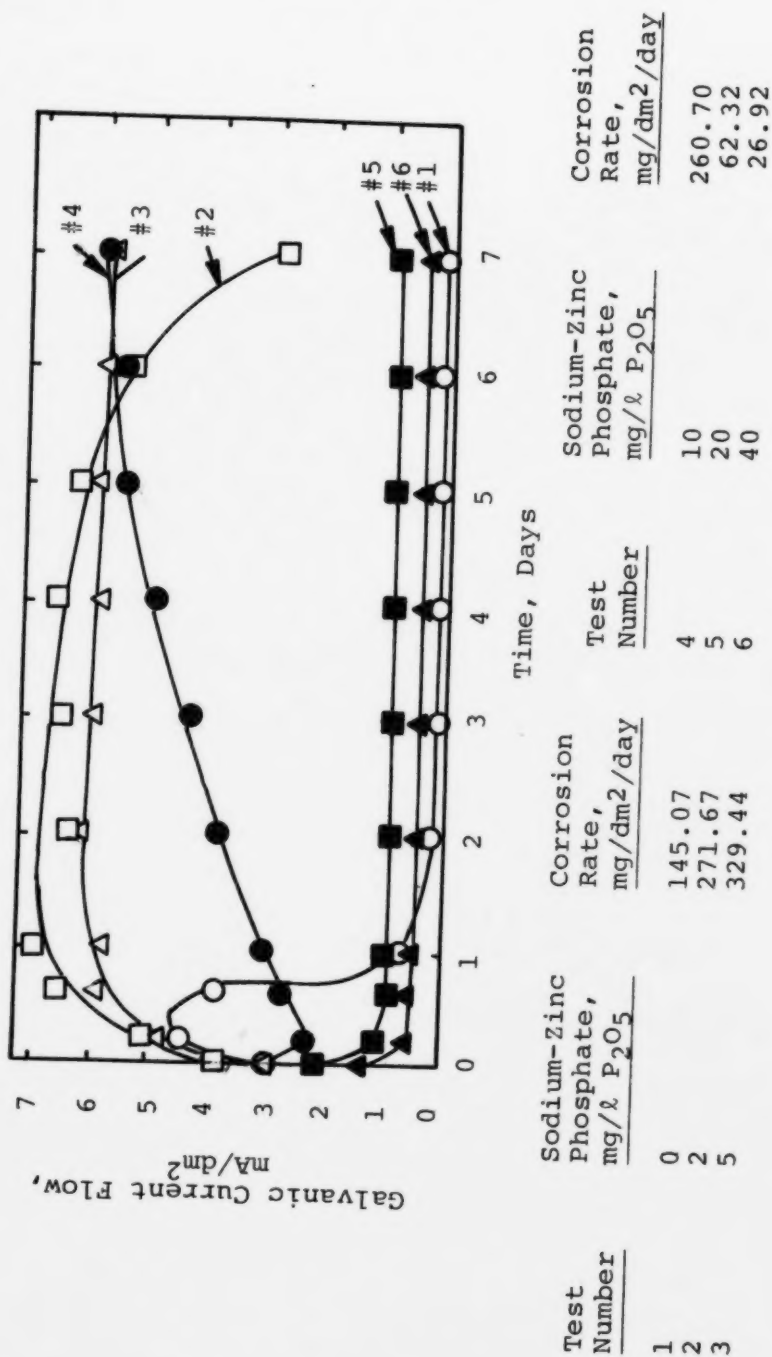


Fig. 91 Effect of Sodium-Zinc Phosphate (Calgon TG-10) Dosage on Galvanic Current Flow and Corrosion Rate in Batch Systems (25°C, University Laboratory Tap Water)

Synthetic Water Compositions:

Chemical	Concentration (mg/l)	Ion Concentration (mg/l)				
		Mg ²⁺	Ca ²⁺	SO ₄ ²⁻	Cl ⁻	Alk.
MgSO ₄ · 7H ₂ O	37.0	15		14.4		
CaCl ₂ · 7H ₂ O	44.0		30		21.2	
NaHCO ₃	50.4					30

Ca²⁺, Mg²⁺ and alkalinity are expressed as mg/l CaCO₃.

The effect of P₂O₅ concentrations on galvanic current flow and corrosion rate were evaluated at six different levels, 0, 2, 5, 10, 20, and 40 mg/l as P₂O₅, respectively. As expected, Figure 92 shows a direct relationship between the corrosion rate of cast iron test specimens and the galvanic current flow of corrosion cells, i.e., the lower galvanic current flow tended to have less corrosion rate of cast iron test specimens.

Moreover, from Figure 91 and 92, in systems without phosphate compounds, the cathodic polarization was evident in systems having the calcium carbonate saturation (not in systems with CaCO₃ unsaturated state). On the other hand, in the phosphate-enriched test systems of P₂O₅ dosages 20 and 40 mg/l, the cathodic polarization was found in both calcium carbonate saturated and unsaturated states. As a result, the rate of corrosion of cast iron test specimens can be effectively reduced by increasing the degree of cathodic polarization in the corrosion cells by the addition of requisite amount of phosphate compound.

J. Mechanism of Corrosion Inhibition by Phosphate Addition

The results obtained during this research, together with those obtained by past investigators, have led to the following general hypothesis concerning the possible mechanism of corrosion inhibition by the polyphosphate compounds tested. Both orthophosphate and condensed phosphates appear to react with cations, such as ferrous, zinc and calcium ion, resulting in the formation of charged colloidal particles. The particle formation appears to be favored by increasing pH, calcium and polyphosphate concentrations. These colloidal particles are subsequently deposited. It is possible that cation-condensed phosphate particles deposited on the cathode play the most important role and may serve as a protective cathode coating. The protective coating thus formed on cathodic areas decreases

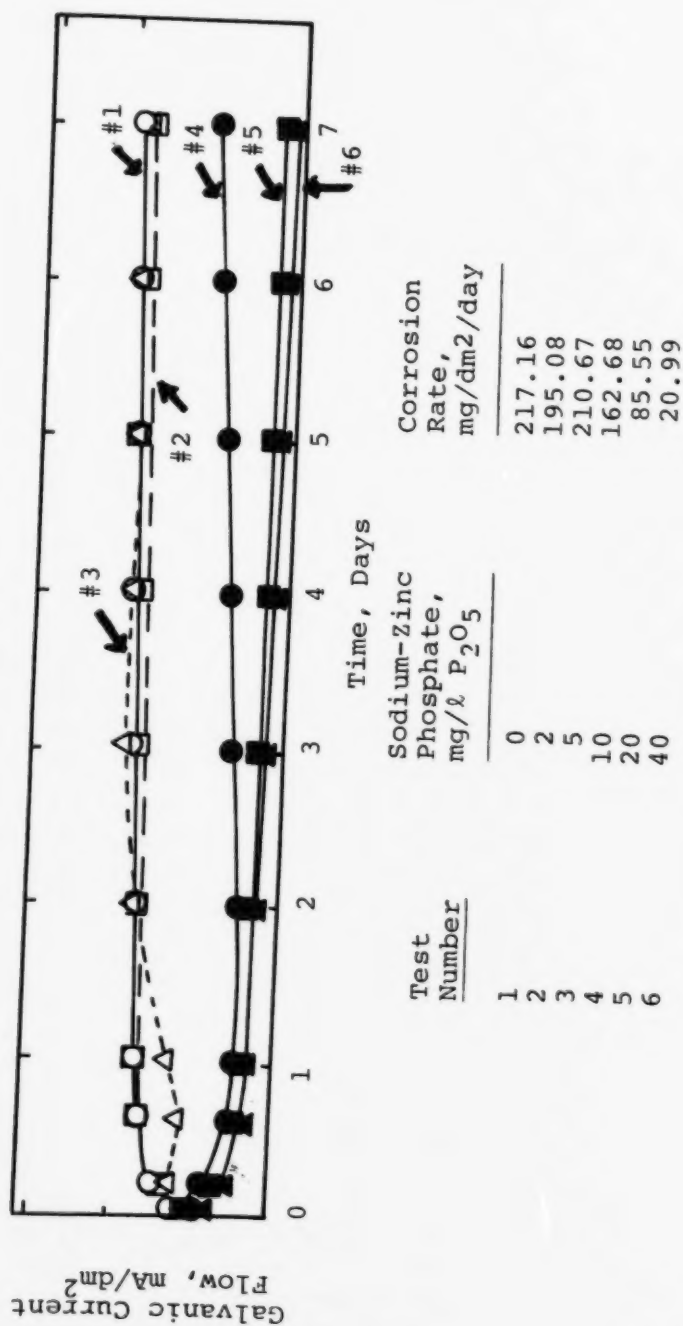


Fig. 92 Effect of Sodium-Zinc Phosphate on Galvanic Current Flow and Corrosion Rate in Batch Systems (25°C; Synthetic Water; pH = 7.8; Ca²⁺ = 0.6 meq/l; Alkalinity = 0.6 meq/l) (Calgon TG-10)

the corrosion rate of cast iron in water by increasing the degree of cathodic polarization in the corrosion cells.

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APPENDIX A

LITERATURE REVIEW

MICROORGANISMS LINKED TO WATER QUALITY CHANGES IN DISTRIBUTION SYSTEMS:

Water quality in distribution systems may be adversely affected either by specific microorganisms or by a variety of organisms involved in different microbiotic cycles. The activity of these organisms will vary with temperature, aqueous chemical constituents and physical characteristics of the water system.

A comprehensive literature citation would be too voluminous if studies were to cite all the specific microorganisms that have been linked to water quality changes in water systems. Thus, only the basic literature pertaining to microbially mediated water quality changes in distribution systems are examined.

Growth of Microorganisms in Water Distribution Systems

Powell (1) in 1921 surveyed 32 municipal water plants and found that 92 percent of these systems had a reported increase in the number of bacteria at the consumer's tap. In addition, the quality of the water drawn by the consumer was quite different from the quality observed immediately after purification. Little effort was made to identify the microorganisms observed in these water supplies.

Initial concern over the presence of microorganisms in drinking water was related to fear of disease. However, with time, water works professionals recognized the importance of microorganisms that affected the aesthetic quality of water.

In 1929, the Committee on Water Supply of the Public Health Engineering Section of the American Public Health Association (2) reported, on the basis of a survey, that a number of cities had severe bacterial aftergrowths in their distribution systems. Schaut (3) reported high bacterial growth in the Philadelphia water system when the temperature was cold and chlorination was least efficient.

Baylis (4) in Chicago, Illinois conducted pioneering experiments to determine the cause of bacterial aftergrowths. He allowed two water taps to flow continuously at 200 ml/min. One system received a chlorine dose of 0.5 mg/l while the other was unchlorinated. He observed significant bacterial aftergrowths in the systems with no chlorine, while the system with chlorine showed low bacterial counts. He also attempted to determine if B. coli (presently known as Escherichia coli) and other bacteria could grow in the sediment accumulated in the water pipes. He found high counts of B. coli in the sediments. Baylis concluded that the sediments present in the water pipes can interfere with the destruction of bacteria by chlorine. Even though the water may contain high levels of chlorine, there would be a region of chlorine-free water within the sediment where bacteria could grow abundantly. He recommended that a systematic flushing of dead-end water mains was necessary to maintain bacterial water quality in a distribution system.

In 1928, Buswell (5) postulated that ammonia and methane in water might be possible substrates for the growth of microorganisms in distribution systems. However, he found that the microorganisms from water pipes did not grow well under artificial laboratory conditions.

In 1944, Shannon and Wallace (6) sampled the water supply system of Detroit, Michigan. They isolated 495 bacterial colonies from samples of dead-ends, consumer complaint areas and chlorinated water plant effluent. Forty-two of these were Gram positive cocci, five, Gram positive rods and 448 Gram negative rods. Of the 448 Gram negative rods, 32.5 percent were of the coliform group, 20.5 percent Alcaligenes; 12.7 percent Pseudomonas, 12.3 percent Proteus; 9.5 percent Eberthella, 4.4 percent Salmonella and 6.9 percent unidentified species. They postulated that either these bacteria had escaped the chlorine treatment or penetrated the system through possible defects such as, main breaks, cross-connections, etc.

Alexander (7) emphasized the importance of maintaining chlorine residuals throughout the distribution system in order to control slime-forming (attached) organisms. Despite a "sterile" finished water, he observed that slime-forming organisms in the distribution system could only be partially controlled. Alexander recognized the effects of microbial interrelationships. He observed Bacillus, Sarcina, Micrococcus, Flavobacterium, Achromobacter, Alcaligenes, Pseudomonas and Proteus genera in water. He believed that the source water was a principal factor in determining the organisms found later in the distribution system.

Similarly, Wilson (8) believed that bacteria originated in the source water and usually became attached to pipe walls.

The microbial colonies then grew on the surface forming encrusting tubercles and slimes. He concluded that it would be impossible to enumerate accurately all the bacteria present in the water.

Wilson felt that the types and numbers of bacteria which develop in a given water distribution system depends upon the environment or particular ecological niche available. Many bacteria which are unable to flourish in a particular environment may survive in a dormant state for indefinite periods. At a later time, with a more favorable change in the environment these bacteria may start multiplying. In general, water distribution piping provides a constantly changing environment, particularly with respect to seasonal temperature changes. Consequently, the prevailing bacterial forms differ from place to place in the system and from season to season.

Wilson's observation of microbial ecology illustrates the symbiotic nature of various bacteria in natural environments. He was the first to shed light upon the cyclic transformation of various elements, such as, carbon, sulfur, iron, manganese, nitrogen and phosphorus in a water system. Such ecological cycles result in a succession of micro-populations in response to the changing environment. Therefore, the microbiology of water pipes should be examined in terms of naturally-growing communities of mixed bacteria, fungi and protozoa in water. Wilson developed a sound basis for studies of water distribution microbial ecosystems. For example, he observed higher concentrations of bacteria on plates incubated in 20°C. He further examined those organisms which may affect the taste and odor qualities of the water. He cited Beggiatoa, Thiobacillus, Crenothrix and sulfate-reducers as those responsible for corrosion of pipes with the production of tubercles. In summary, Wilson believed that no water supply was free from bacterial growth problems because all waters contained sufficient substrate to support the active growth of a community of microorganisms.

Recently, Geldreich, et al. (9) reported on the bacterial flora in public water supplies. They stated that the bacterial flora in water supplies originates from the source water. The initial bacterial population may be drastically reduced through chemical treatment and filtration. With the application of a disinfectant, the residual population is further reduced. As a result, the treatment process becomes selective for microbial species. The residual population may include some Gram positive and negative organisms, acid-fast organisms, Actinomycetes, yeasts and fungi. Other microorganisms may also penetrate the treatment barrier along with turbidity or during temporary lapses in treatment. According to these researchers, a number of possible defects may contribute to the microbial population of a distribution system. These

include: (i) cross-connections; (ii) improperly protected distribution storage; (iii) improperly located sewer lines at nearby water mains; (iv) improperly constructed air relief valves; (v) inadequate main disinfection; (vi) low or negative pressure; and (vii) regrowth in pipe sediments. Regardless of their initial source, microorganisms can proliferate in a water distribution system and effect water quality changes. As pointed out by these authors, the standard plate count enumerates only a part of the total microbial population in water systems. The concern for bacterial regrowth is especially critical in that there might be a possibility that the resulting high bacterial population can suppress the observed coliform count and permit the survival of waterborne pathogens.

Recent characterization studies by these researchers on the bacteria included in the standard plate count from three water distribution systems indicated that most of the strains isolated belonged to the enteric Gram negative group (9).

Microorganisms that Influence Taste and Odor

From the standpoint of the consumer, an unpleasant taste and odor in drinking water is the most uncompromising adverse quality. The water works profession has long been aware of this fact. Even prior to the 1900's, these problems were widely discussed at technical meetings.

In 1897 Leeds (10) reported the problems of taste and odor affecting the Brooklyn water supply. Even at that early date, he recognized these problems to be due to microbial growths in the system. Other earlier reports which related taste and odor problems to the microbial growths in the system include those of Baylis (11), Kofoed (12), Moses (13), and Lendall (14).

Baylis (11), one of the research pioneers in the water works profession, reported on the problems of microorganism growth in the Baltimore, Maryland, water supply. Having observed a variety of organisms, including algae, diatoms, protozoa and bacteria in the system, he expressed concern for the lack of attention being given to microbial growths in water systems. He noted a significant increase in bacterial concentrations in winter months. He concluded that the decaying algae and diatoms had provided nutrients for these "scavenger" bacteria. It was inferred, from Baylis's work, that microbiotic cycling of nutrients between algae, diatom and bacteria took place in water systems. Taste and odor problems may have been caused by both algal by-products and bacterial growth.

Kofoed (12) also noted the origin of odors due to the growth of algae in reservoir waters. He emphasized the importance of maintaining high quality source water in alleviating

the taste and odor problems in the potable water.

In 1946, Lendall (14) made a comprehensive survey of the taste and odor problem. He related causes of taste and odor to algae and proposed two remedial methods, the removal of tastes by activated carbon treatment and the prevention of algal growth by breakpoint chlorination and chlorine dioxide treatment.

Since many water systems obtained their raw water from surface water supplies, many investigators have observed the occurrence of algae, protozoa and bacteria in surface waters (14,17). Palmer and Tarzwell (15) and Palmer (16) described the algae of importance in water supplies. In these papers, the authors dealt with the algal groups which were responsible for natural colors as well as those important in water supplies.

In 1961, Palmer (17) wrote an excellent review of algae and other interference organisms in water supplies. His comprehensive review also dealt with those microorganisms that have been directly associated with water quality deterioration in distribution systems, including iron bacteria and protozoans. Although his report mainly consisted of California incidences, the basic factors involved in infestation of microorganisms in distribution systems are applicable to other regions as well.

The types of bacteria in water, with the exception of those that directly relate to the public health aspects of water supplies, were not seriously studied before 1960. Investigations on the terrestrial (18) and aquatic (19) actinomycetes were made, but accurate knowledge of the biological processes in water systems was lacking.

From his studies with aquatic actinomycetes, Silvey (19,21) concluded that both algae and actinomycetes were responsible for taste and odor problems in water supplies. In 1964, Silvey and Roach (20) reviewed various aspects of microbial interrelationships that comprise the microbiotic cycles. In particular, they explained how these microbiotic cycles might contribute, directly or indirectly, to the taste and odors in water supplies in certain parts of the United States.

Increases in Gram-negative organisms were noted by Silvey and Roach (20). This observation confirmed Baylis's earlier observations in the Baltimore, Maryland, water system (4). Generally, Alcaligenes, Aerobacter and Pseudomonas groups were found in water with little pollution. Field data substantiated the hypothesis that microbiotic cycles of blue-green algae, actinomycetes and heterotrophic bacteria were responsible for taste and odor problems in water.

Recently, Lin (22,23) reviewed tastes and odors in water

supplies. He had discussed sources of tastes and odors in water which included by-products produced from algae as well as decaying materials of aquatic organisms. He also emphasized man-made substances that were sources of tastes and odors.

Microorganisms that Accumulate on Pipe Walls and Promote Tubercle Formation

In 1897, Whipple (24) made observations on the growth of organisms in water pipes. He based his observations on eight years of data from the Boston Water Works. Water intakes from both reservoirs and two locations in the distribution system were the sample sites for the data analysis. He noted changes in temperature, organism density and "amorphous matter" in distribution water samples. The greatest range of temperature change occurred at two reservoirs with seasonal temperature change. Whipple observed changes in organism densities in distribution system samples in that they were lower than those observed in reservoir samples.

Whipple did not classify the organisms he observed in his study, but his description of the organisms indicates algal groups. He also discussed the occurrence of Crenothrix in water systems in Europe. Apparently, the problems of iron bacteria, Crenothrix, in water systems had not been reported or investigated in the United States at that time. In his investigation of the Boston Water Works distribution mains, Whipple found tubercles as well as a large, thick (1/4 inch) brownish mat from a section of main which had been taken out of the system. Whipple identified the brownish mat as Polyzoa, a sponge, which might have entered the distribution system from the water source (two reservoirs) and thrived on organisms in the water pipes. He concluded that the concentration of organisms in the distribution systems had decreased possibly due to the sedimentation of cells plus decomposition by the Polyzoa specie in the water system. The significance of this early observation was that any microorganisms which can enter the water system may be a potential mediator for water quality changes in the distribution system. Tuberculation was recognized as an inherent problem in water pipes, but was not perceived as important in pipe corrosion.

After the turn of the century, numerous investigations were devoted to the elucidation of corrosion, tuberculation and the role which iron bacteria might play in water pipes (25).

One of the first investigators who reported the problem associated with iron bacteria, Crenothrix kuhniana (now renamed as Crenothrix polyspira by R.S. Wolfe (49) in water supplies was E.G. Smith (25). He had found accumulations of iron bacteria in various water pipes. O.T. Smith (26) reported a case

study in Freeport, Illinois, concerning taste and odor problems in drinking water. Microbiological analysis indicated that the yellowish-brown floating matter in the water was a *Crenothrix* species. Concurrently, O.T. Smith observed significant increases in the iron concentrations in water mains, particularly, in dead-end areas. The iron concentration of filtered water averaged 0.045 mg/l, while water at the pumping station averaged about 0.796 mg/l. However, the iron concentration of water samples taken from the distribution system ranged from 0.4 - 19.2 mg/l. For a remedial measure, Smith recommended a thorough flushing of the entire distribution system.

Van Giesen (27) believed that various salts in potable water also could contribute to the formation of tubercles and red water. It was clearly evident that corrosion of water pipes could result in serious problems of red water at the consumer's taps, and loss of hydraulic capacity as well, due to the formation of tubercles. In 1939, Larson (28) reported a case study of a distribution system where iron bacteria might have influenced the iron corrosion and resulted in red water problems in the distribution system. In this case study, the water leaving the plant was iron-free. Iron concentrations in the distribution system increased to as much as 8 mg/l. Williams (29) and many others (30-32) were concerned about the problem of internal pipe corrosion and the resultant tuberculation on pipe walls. Other investigators reported on the various control methods available (33-35). Methods cited included chlorination, chemical additions or main flushing to control microbial growth. These methods sequestered the iron or physically removed the accumulations from the water systems.

In 1945, Starkey (36) prepared a comprehensive review on the subject of the transformation of iron by bacteria. He pointed out that some of the iron transformation is brought about by bacteria having specific physiological characteristics intimately associated with iron transformation. With other organisms, iron transformation was only incidental to the normal development of the bacteria. Iron bacteria which can oxidize ferrous iron to ferric iron and effect the precipitation of ferric hydroxide belonged to the first group. The latter group included any bacteria which could cause changes in the iron concentration of the water by altering the environmental conditions. Still other bacteria, such as sulfate-reducing bacteria, were known to be associated with bacterial corrosion, specifically, anaerobic corrosion.

As a result of their metabolic activities, microorganisms which grow on the surface of iron, may bring about certain altered conditions. A common occurrence on the interior walls of water pipes is the development of tubercles. A tubercle may consist of mass of corrosion products and microorganisms.

J.R. Baylis (37), who had earlier noted the microbial growths in the Baltimore, Maryland water system, made a detailed study of many tubercles from the distribution mains. He found that the pH of the water in an active tubercle was about 6 while it was slightly higher (6.4 to 6.8) in those tubercles that were dormant. The pH of the treated City water was 7.9. An active tubercle contained microorganisms, whereas the dormant one did not.

Baylis observed that negative ions, such as chlorides and sulfates, were materially concentrated in the tubercles and that the black ferrous-ferric hydroxide was magnetic and tended to become attached to the metal in the form of columnar porous fibers. The non-filamentous bacteria, Gallionella, and the filamentous types, Crenothrix, Clonothrix, Leptothrix, Sphaerotilus were among the principle types isolated from the tubercles. Calculations indicated that the growth of these iron-precipitating bacteria utilizing ferrous iron in solution could produce about 500 times as much precipitate of ferric hydroxide as could cells of the true iron bacteria.

According to Olsen and Szybalski (38), the extent of bacterial involvement in the aerobic corrosion was limited to the production of the felt-like structure of sheath which comprised tubercles. They conducted experiments with iron bacteria, Leptothrix, in a continuous flow of tap water through pipes, to evaluate their proposed theory of aerobic iron corrosion involving microorganisms. They found that sterile water did not cause tubercle formation while the iron bacteria caused both tubercle formation and corrosion. The presence of iron bacteria resulted in an average increase in corrosion rate of about 10 percent. In regions where the bacteria were deposited, the potential of the iron decreased rapidly, establishing a primary microdifferential aeration cell on the pipe surface. Corrosion and tubercle formation by the precipitation of hydrated ferric oxide started immediately. Simultaneously, the bacterial colonies grew. After the tubercles had formed, the iron bacteria played practically no role in the progressing corrosion.

The role which iron bacteria played in stimulating the corrosion of iron did not appear to be a permanent one, for even though the bacteria had died, the corrosion of iron ensued. Thus, these authors concluded, destroying the iron bacteria after tubercles have been formed would not inhibit the further corrosion of pipe walls. Tubercle formation by iron bacteria appeared to be a critical factor in the internal corrosion of iron pipes. In fact, microorganisms might be a primary cause of corrosion in new pipes. Using the same line of reasoning, any microorganisms which can induce the tubercle formation on pipe walls might be the potential stimulators of the corrosion of iron pipes.

During the 1950's and 1960's, pipeline corrosion due to the profuse growth of the filamentous iron bacteria had been widely recognized both by the utility managers and other water works professionals (39). In California, Wilson referred the episodes as "water calamities" (40). Crenothrix was the most important and predominant filamentous form of iron bacteria that plagued water systems. A main flushing program to remedy the situation still left a layer of slime organisms on pipe walls. Therefore, a three year program of chlorination and frequent systematic flushing procedures were conducted to remove the detached growths and accumulated detritus from the invert of the pipes.

San Francisco, California, had serious trouble with iron bacteria in the Hetchy tunnels where the carrying capacity of the conduit was reportedly reduced as much as 20 percent (8). Inspection disclosed a slimy, gelatinous, light brown growth covering the entire inner surface of the pipe up to 0.25 inch thick. Palo Alto received over 1200 consumer complaints because of red water and foul odors resulting from the Crenothrix infestation of the distribution system (41).

A case in Torrance, California was reported by Pomeroy and Montgomery (42). The well water had no oxygen but contained methane and hydrogen sulfide. When growth was found in the distribution mains, chlorination was initiated. Eight years of chlorination resulted in improved conditions. The authors claimed that chlorine acted to reduce the biological oxygen demand of the water and to maintain aerobic conditions in water mains.

Analysis of water at dead-ends of the Chicago distribution system had indicated that bacteria were protected from chlorine by pipe sediments (43). Others also reported that residual chlorine and chloramine were reduced or consumed because chlorine had reacted with iron (44,45). The corrosion of iron had resulted in the decrease of residual chlorine accompanied by a corresponding increase in the ferrous iron concentration in water.

As an index of corrosion and corrosion control, Barbee (46) measured tubercle effects. He assumed that the tubercle formation on pipe walls would result in a greater loss of flow due to these protuberances. Consequently, the measurements of the head loss through the pipe sections should directly reflect the corrosive character of the raw and the treated water. He used the treated water with a corrosion inhibitor, sodium hexametaphosphate, and compared specimen loss and pipe head loss with that for raw water. He found that the difference between the best treatment and the next best treatment was only 0.2 - 0.5 mg/cm²/week less weight loss. The weight loss of specimens in raw water was 4.7 mg/cm²/week. As expected, the greater head loss was observed in the system with the

higher corrosion rate. He found iron bacteria, *Leptothrix*, in the storage tank and a decrease in the dissolved oxygen concentration of about 0.4 mg/l.

The problem of bacterial growth and the associated water quality deterioration in distribution systems is not exclusively related to filamentous iron bacteria. Wilson reported that a 96 inch conduit had lost 10 percent of its carrying capacity due to saprophytic bacteria that produced slime growths. A case study in Santa Rosa, California was reported by Brown (47). The city obtained its water from two separate water sources, lake and well water. The well water was subject to extensive problems with slime formation, discoloration and offensive odor. Hydrant flushings showed severe discoloration and heavy accumulation of solid particles, somewhat slimy in appearance. Its color ranged from brown to gray and black. Musty to septic odors were noted characteristic of growths of slime-forming, non-filamentous bacteria. A significant water quality change was the almost instantaneous depletion of dissolved oxygen. Five to six mg/l of dissolved oxygen was consumed within 15 minutes. Biological influences on water quality were confirmed when the water was treated with three mg/l of free residual chlorine followed by a thorough flushing of the distribution system. Within a few weeks, slime accumulations were eliminated while no appreciable loss of the dissolved oxygen and chlorine residuals were observed.

In 1962 Lueschow and Mackenthun (48) examined 76 Wisconsin municipal well waters to enumerate iron bacteria. They detected *Gallionella* and *Leptothrix* in 35 well waters. Iron concentrations of the well water had no apparent relation to the presence of iron bacteria. Iron concentration of well waters that contained iron bacteria averaged 0.51 ± 0.28 ppm. Even within the same well wide variation in iron concentrations was observed. The number of iron bacteria found in the distribution system was generally under 100 per ml. However, two outlets, i.e., a hydrant and a relatively unused tap yielded dense red sediments and 10^7 iron bacteria per ml.

The microbial concentration of waters with low concentrations of iron and manganese was investigated by Wolfe (49). He observed a large sheathed bacteria which can concentrate iron and manganese in its sheaths and flourish in a water supply containing no detectable manganese and less than 0.02 ppm of iron. Hairlike clumps and dark gray-brown flocculent clumps were identified as *Clonothrix putealis*. He analyzed 40 mg of dried deposits and found 69.32 percent organic matter, 9.8 percent ferric oxide, 12 percent manganese oxide, 8.8 percent silicon oxide and 0.08 percent phosphate. Wolfe's observation indicated that sessile organisms can concentrate iron and manganese from a large volume of water even though the

bulk water that flows over them contains only trace amounts of the metals.

In 1970, Shindala and Chisholm (50) observed water quality changes in the Jackson, Mississippi distribution system. They sampled water from selected fire hydrants of the distribution system and concluded that, at normal low flow, iron and manganese slimes may be deposited in the distribution system without being detected by the consumers. However, high velocity surges in pipes can cause these deposits to slough off and appear at the consumer's tap. If iron bacteria are present in the well water source, regardless of the type of pipe, the discoloration problem would be observed.

Although they are not true iron bacteria, many heterotrophic bacteria precipitate iron from solution (51-53). Many microbiologists searching for iron bacteria in the precipitates microscopically have found the presence of aggregated bacteria encrusted with ferric-hydroxide instead of the usual filamentous iron bacteria. Species of Eubacteriales which were found to be able to precipitate iron from the salts of organic acids include Enterobacter, Bacillus, Pseudomonas, Serratia, Flavobacterium and Mycobacterium species. The ferric hydroxide is apparently a waste product and iron salts are a necessary metabolite for these forms. Microorganisms may create a reducing environment by forming metabolic end products which can also act as reductants of iron and manganese oxidation.

Macrae and Edwards (53) examined seven genera of bacteria by electron microscopy. The objective of their study was to evaluate iron-precipitating organisms. All species examined precipitated the iron from aqueous solution and the bacterial cells became encrusted with iron. Bacteria adsorbed iron from a positive iron sol. The precipitation of iron was completed after 20 minutes with Pseudomonas, and Mycobacterium phlei. The stalk and holdfast of Caulobacter species showed considerable adsorption of the colloidal iron and positively charged colloidal iron in surface water. The authors related the importance of iron deposition in surface water supplies.

Although not much is known about the manganese-depositing microorganisms, Hyphomicrobium and Gallionella species have been associated with manganese deposits in water pipelines (54-57). Hyphomicrobium grows in waters with small amounts of organic matter. Some iron bacteria also are known to precipitate both iron and manganese oxides. If a water source contains a significant concentration of both manganese and iron, its water carrying capacities might be substantially reduced due to the precipitation of both metal oxides. Clonothrix and Crenothrix species can both precipitate iron and manganese oxides.

In 1964 Mulder (58) reviewed the behavior of slime-forming microorganisms, including iron bacteria, particularly those of the *Sphaerotilus* - *Leptothrix* group. The author discussed isolation, cultivation and ecology of iron bacteria. More importantly, information concerning iron bacteria in relation to iron and manganese compounds was collated and discussed by the author.

According to Miller and Litsky (59) the bacteria native to natural waters may be classified as the sheathed higher bacteria, stalk or caulobacteria, the spiral forms, the pigmented and non-pigmented rods, the cocci, the nitrogen-fixing and nitrifying bacteria. These organisms are also found in water distribution systems.

Recently Ainsworth (60) examined the chemistry and microbiology of the water and deposits in fourteen United Kingdom distribution systems. He found that the processes of precipitation and deposition were frequently the result of poor or insufficient treatment of the raw water. Progressive water sampling through the distribution system revealed decreases in silica, algae, manganese and dissolved organic matter. These components tended to concentrate in loose sediments and the more readily disturbed surface layers on pipe and tubercle surfaces.

Ainsworth found a positive correlation between the bacterial numbers and the decrease in organic carbon through the distribution system. Ainsworth further observed that plate counts (Yeast Extract Agar, 7 days at 22°C) greater than 10^3 per ml were frequently associated with an observable deterioration in water quality, such as depletion of dissolved oxygen and increased levels of turbidity. He also found that bacteria are in greater numbers in sediments and precipitated layers than in corrosion products and that the surfaces of corrosion tubercles supported more bacteria than the contents, including anaerobic organisms. He noted that dissolved oxygen depletion greater than 15 percent was often associated with poor quality and consumer complaints.

Allen, *et al.* (61), using a scanning electron microscope, showed that within protective encrustations or tubercles inside a distribution system, colonization of microorganisms can occur. The formation of these tubercles is affected by many physical, chemical and biological factors within the pipes.

Touvinen, *et al.* (62) examined tubercle deposits collected from pipelines in the Columbus, Ohio distribution system. The examination included a microbiological, chemical and mineralogical analysis. Microbiological analysis revealed that the tubercles contained several kinds of organisms, including sulfate reducers, nitrate reducers, nitrite oxidizers, ammonia

oxidizers, sulfur oxidizers, and various unidentified heterotrophic microorganisms. Chemical analysis showed that the tubercles consisted largely of iron oxides, with varying quantities of trace elements.

Microorganisms that Produce Mineral Acid and Promote Corrosion

Although little is known about the activities of sulfur-oxidizing organisms in water system, the deleterious effects of these organisms are known. Parker (63) conducted extensive studies on the detrimental effects of sulfur-oxidizing organisms in the corrosion of concrete sewer pipes.

The sulfur bacteria, as a group, are characterized by their ability to oxidize reduced sulfur to sulfur crystals or sulfate ions. Morphologically, sulfur bacteria vary from the complex filamentous Beggiatoa and Thiothrix species to the simple rod form, Thiobacillus species. The filamentous sulfur bacteria are typical water organisms and are encountered together with iron bacteria in water basins or in water distribution systems. Beggiatoa has caused much trouble in several suburban areas of Los Angeles (17). Although sulfide was not detected at the treatment plant, Beggiatoa was present in the distribution system.

The thiobacilli are a group of aerobic or facultative anaerobic autotrophs which obtain their energy for carbon dioxide fixation by a series of reactions involving the oxidation of reduced sulfur to sulfate. Thiobacilli are fairly common soil organisms, and yet, their attack on ferrous metals has not been reported frequently in the literature. Occasionally, the corrosion of iron pipelines associated with very high concentrations of sulfuric acid has been reported (64).

Microorganisms Associated with the Anaerobic Biological Corrosion of Iron

The possibility that microorganisms might influence the corrosion of metals was first mentioned by Garrett in 1891 (65). He suggested that the increase in the corrosion of metal lead might be due to the ammonia, nitrites and nitrates produced by bacterial action. Then in 1910, Gains (66) postulated that the corrosion of iron in soil and aqueous environments might be caused by organisms such as sulfate-reducing, sulfur-oxidizing and iron bacteria. The iron bacteria, Gallionella ferruginea was isolated from corrosion products on a buried steel conduit. High concentrations of sulfur and organic matter were also noted. However, Gain's proposal of biologically mediated corrosion was not accepted initially.

In 1923, von Wolzengen Kuhr (67) showed that the activities of sulfate-reducing bacteria can result in the corrosion of

iron in the absence of oxygen. Further evidence of anaerobic corrosion was presented by von Wolzogen Kuhr and Van der Vlugt (68). In a comprehensive Dutch publication they attributed the theory of graphitization of cast iron pipes to the detrimental activities of sulfate-reducing bacteria.

In the United States confirmation of the role of these anaerobic bacteria in the corrosion of iron pipes resulted from the studies of Hadley (69) and Starkey and Wight (70).

Hadley investigated the corrosion of pipelines in Pennsylvania, Ohio and New York. He found a good correlation between the corrosion rate and the type of soil in which the pipe was buried. Corrosion was at its worst in low, swampy areas where the soil pH ranged between 6.2 and 7.8. In such areas pipelines lasted only seven years due to the corrosion. Examination of the corroded pipes showed a black mass which consisted of ferrous hydroxide and ferrous sulfide. A cultural test showed sulfate-reducing bacteria in soil samples.

In 1941, Pomeroy (71) reported an interesting case where an eight inch cast iron pipe became nearly filled with corrosion products consisting principally of iron sulfide and iron oxide. After 13 years, only a three inch opening remained. The conditions under which the corrosion occurred and the nature of the corrosion products suggested that there had been anaerobic corrosion.

Drinking water from surface water is generally well oxygenated. Therefore, it might seem unlikely that conditions would prevail for development of anaerobic bacteria in water distribution systems. However, the encrustations which iron bacteria and other microorganisms form on the insides of water pipes could harbor sulfate-reducing bacteria and permit corrosion attributable to these organisms (72)(73).

Pomeroy (72) observed that iron corroded faster when it was exposed to water intermittently with and without oxygen than when it was exposed to water constantly without oxygen.

Butline, *et al.* (73) found approximately 10^3 sulfate-reducing organisms per gram of tubercles obtained from the Barnsley Waterwork Department in England. Earlier, Bunker (74) has reported isolating sulfate-reducing bacteria in tubercles.

Lewis (75) reported a case history of a midwestern U.S. city which had problems with rusty water. A main inspection showed tubercles in parts of the line. Chemical analysis of the treated water showed 0.6 mg/l of iron and a high concentration of sulfate ion. Water and solid samples, including both the treated water at the treatment plant and at the distribution system and the tubercles, were examined for sulfate-

reducing bacteria. Lewis found 2.8×10^4 organisms per gram of tubercle, while there were no detectable sulfate-reducing organisms in the water.

It is evident that most literature published concerning microorganisms and the internal corrosion of pipe surfaces have dealt with either iron bacteria or sulfate-reducing bacteria.

WATER QUALITY CHANGES IN DISTRIBUTION SYSTEMS AS AFFECTED BY CORROSION

Distribution System water quality may also be adversely affected by chemical or biochemical corrosion of metal components comprising the system. The corrosion phenomenon is extremely complex and the literature pertaining to corrosion is quite voluminous. In this review only the literature related to corrosion prevention in water distribution will be considered.

General Aspects of Corrosion Mechanism

Corrosion is the destruction or deterioration of metal by direct chemical or electrochemical reaction with its environment.

The classic work of U.R. Evans (76) established that basically all corrosion phenomena of metals in aqueous environments are electrochemical in nature. Two distinct, but related, processes comprise the corrosion reactions: anodic (oxidation) and cathodic (reduction) reactions. The conditions under which an electrochemical reaction can take place depend essentially on the relative values of the electrode potential of metal and the thermodynamic equilibrium potential of the reaction. A metal whose corrosion products are in a lower energy state than the metal would tend to convert (corrode) to its products. Iron and steel which make up the majority of the potable water system are such metals and thus have tendency to dissolve in aqueous solution.

Evans and his group (77) at Cambridge had measured the quantity of current flowing between anodic and cathodic areas on specimens partly immersed in water. They found that a direct correlation existed between the quantity of current flowing and the weight of metal dissolved. Variations in temperature, oxygen concentration and ion concentration at the surface of a metal contributed to establishing electrical currents which subsequently resulted in metal corrosion.

Subsequently, Mahato, *et. al.* (78) confirmed the general relationship between potentials and corrosion rates. These investigators observed the rapid change of potential in the

anodic direction corresponding to a high initial corrosion rate. The potential gradually became more cathodic with time and approached a constant value.

The corrosion of iron in an aqueous environment was observed with dissolved oxygen in solution. Evans related the amount of corrosion to the amount of oxygen uptake. He thereby provided a theoretical basis for the mathematical expressions of iron film growth which was produced as a result of corrosion in oxygen environment.

Pourbaix (79), who emphasized the necessity for understanding the chemical fundamentals of the corrosion mechanism, established a method for predicting metallic corrosion under various thermodynamic conditions. Pourbaix utilized a pE-pH* diagram to conveniently represent the oxidation states and regions of thermodynamic stability of different metals and their insoluble salts.

Pourbaix conducted a number of experiments to verify the corrosion process and to evaluate whether or not the corrosion phenomena observed could be explained by known thermodynamic data. He conducted experiments on the anodic and cathodic polarization of iron to determine the influence of pH on the "passivation potential" of the metal. Results indicated, for example, that protective film could be formed on a ferrous metal when Fe_2O_3 was stable in aqueous solution. Experimentally determined passivation regions confirmed the theoretical regions of passivation.

Using a modified Pourbaix diagram, Bouet and Brenet (80) demonstrated the pH-potential regions of corrosion of iron in an aqueous environment containing sulfide ion (Figure 1). The region of assumed "passivity" (metal insolubility) in the presence of sulfide extends over a larger range of potential and pH than that for passivation by oxygen. It would appear, then, that corrosion is less likely where sulfide is present. However, the passivating sulfide films do not form as effective a barrier to continuing corrosion as do the oxide films. The presence of sulfide ions in the environment of a metallic structure therefore results in prolonged corrosion of unprotected metal. Moreover, the presence of the sulfide film would render alternate surface protection against corrosion more difficult to apply. For example, the presence of solid iron sulfide on the metal surface depressed the potential required for protection to -1.1 Volts (81). Normally, the potential considered adequate for cathodic protection at pH 7 is -0.85 to -0.95 Volt (Cu/CuSO_4 electrode). In the presence of sulfides,

* pE: negative logarithm of the potential of equilibrium, E, of each of the reactions considered

a potential of -1.1 Volts or less is necessary to attain the immunity potential. The formation of high concentrations of sulfide ions around iron metal is of special concern, since it is difficult to detect the onset of such conditions and to protect the metal adequately.

Camp and Meserve (82) explained the corrosiveness of water in terms of half-cell reactions (Table 1). According to these authors a hydrous ferric oxide film may be formed at the anode, provided that the potential of water is about +2.5 to +2.86 volts and pH between 4 and 10. Under normal conditions, water would not reach this high potential. If it did, the formation of hydrous ferric oxide would take place as the cathodic reaction. If the hydrated ferric oxide film remained intact on the metal surface, the metal would become passive and could no longer take part in active corrosion processes. The half-cell reactions which Camp and Meserve have cited have not all been verified in potable water systems. However, the formation of precipitates (hydrated ferric oxides, ferrous and calcium carbonates) in water systems have been confirmed.

Experiments by Larson and King (83) furnished confirmatory evidence for some of the reactions. In their work experimental corrosion cells were devised with an iron electrode. Tap water with pH of 7.4 and an alkalinity of 6.6 meq/l was used for the electrolyte. The water had 1.2 meq/l calcium, 0.48 meq/l of magnesium and 6.0 mg/l of dissolved oxygen. Electric current was allowed to flow through the cell in one direction and ion migration was examined. Results indicated increases in pH to 11, decreases in calcium and magnesium with relatively little change in the alkalinity. The deposition of ferrous carbonate at some anodic points along with the solution of ferrous ions at other anodic points was detected. Since the investigators did not measure dissolved oxygen and ferrous ion concentration, the changes could not be evaluated.

Corrosion Control by Polyphosphate Additions

The principal chemical methods used for corrosion in water distribution systems employ polyphosphates, silicates and calcium carbonate. Since evaluation of polyphosphates as corrosion inhibitors was included as a project objective, a brief literature review is included here.

Mechanism of Corrosion Inhibition by Polyphosphate Compounds

In order to obtain a proper evaluation of the effectiveness of polyphosphate "glasses" as corrosion inhibitors, it is necessary to determine the inhibitory mechanism.

In 1940, shortly after the introduction of metaphosphates as corrosion inhibitors, Hatch and Rice (84) advanced the theory

Table 96 Corrosion of Iron in Fresh Water
[by Camp and Meserve, (82)]

Principal Anodic Reactions:

1. $\frac{1}{2} \text{O}_{2\text{aq}} + 2\text{H}_2\text{O} + \text{Fe} \rightleftharpoons \text{Fe}(\text{OH})_3 + \text{H}^+ + \text{e}^-$ +2.37
2. $\text{Fe} \rightleftharpoons \text{Fe}^{++} + 2\text{e}^-$ +0.440
3. $\text{CO}_3^{--} + \text{Fe} \rightleftharpoons \text{FeCO}_3 + 2\text{e}^-$ +0.755
4. $2\text{OH}^- + \text{Fe} \rightleftharpoons \text{Fe}(\text{OH})_2 + 2\text{e}^-$ +0.877
5. $\text{HSiO}_3^- + \text{Fe} \rightleftharpoons \text{FeSiO}_3 + \text{H}^+ + 2\text{e}^-$ +0.567

Principal Cathodic Reactions Involving Iron:

6. $\text{Fe}(\text{OH})_3 \rightleftharpoons \frac{3}{4} \text{O}_{2\text{aq}} + \text{Fe}^{++} + \frac{3}{2} \text{H}_2\text{O} + 2\text{e}^-$ -1.386
7. $3\text{Cl}^- + \text{Fe}(\text{OH})_3 \rightleftharpoons 3\text{HOCl} + \text{Fe}^{++} + 5\text{e}^-$ -1.58

Principal Cathodic Reactions—Any Metal:

8. $\text{H}_{2\text{gas}} \rightleftharpoons 2\text{H}^+ + 2\text{e}^-$ 0.00
9. $\text{MgCO}_3 + \text{OH}^- \rightleftharpoons \frac{1}{2} \text{O}_{2\text{aq}} + \text{Mg}^{++} + \text{HCO}_3^- + 2\text{e}^-$ -0.822
10. $\text{CaCO}_3 + \text{OH}^- \rightleftharpoons \frac{1}{2} \text{O}_{2\text{aq}} + \text{Ca}^{++} + \text{HCO}_3^- + 2\text{e}^-$ -0.798
11. $\text{H}_2\text{O} \rightleftharpoons \frac{1}{2} \text{O}_{2\text{aq}} + 2\text{H}^+ + 2\text{e}^-$ -1.272
12. $\text{Cl}^- + \text{H}_2\text{O} \rightleftharpoons \text{HOCl} + \text{H}^+ + 2\text{e}^-$ -1.49
13. $\text{Mg}_3(\text{PO}_4)_2 + 2\text{OH}^- \rightleftharpoons \text{O}_{2\text{aq}} + 3\text{Mg}^{++} + 2\text{HPO}_4^{--} + 4\text{e}^-$ -1.443

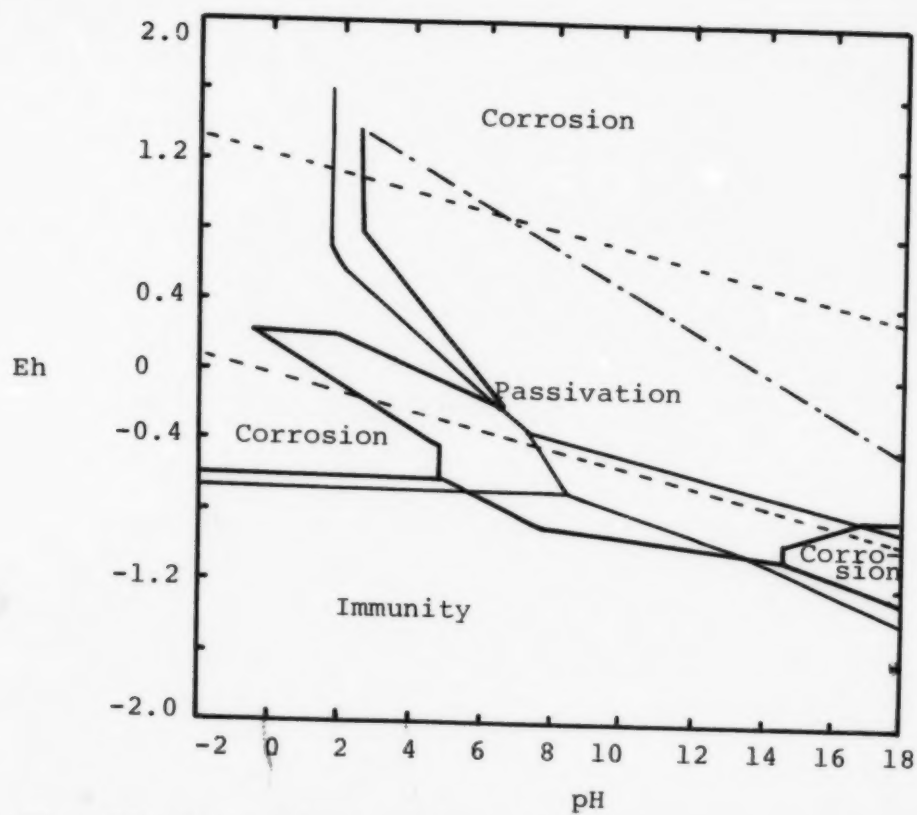


Fig. 93 The Regions of Immunity, Corrosion and Passivation for the Fe-H₂O System (Fine Lines) and for the Fe-S-H₂O System (Broad Lines). (81)

that the inhibitory action was due to the formation of a protective film of metaphosphate on the metal surface. Ten years later, Mansa and Szybalski (85) concluded that the inhibitory action of metaphosphate in differential aeration cells, was due to the formation of a protective film on the cathodes, resulting in reduced cathodic potentials. In 1946, Evans (77) stated that metaphosphate was adsorbed on the calcium carbonate protective coating and served to stabilize it.

In general, metaphosphate "glass" forms negatively charged colloidal particles when placed in distilled water. However, some of the metaphosphate in solution must form positively charged complex ions or colloids before electrical attraction to the cathodes takes place. The presence of divalent cations in solution and its complexation would favor the formation of these particles. Hazel (86) reported that the formation of these positively charged colloidal particles was favored by reductions in pH and increases in the iron oxide-metaphosphate ratio. Hatch (87) has suggested that electrodeposition, also called electroplating, is defined as the process where a part to be coated is immersed in a solution of the metal to be plated and a direct current is passed between the part and another electrode.

Some investigators inferred that metaphosphate should be classified as a cathodic inhibitor under practical conditions (88). Others have reported it as an anodic inhibitor (89). It has been reported (90) that most metaphosphates are deposited at anodic sites.

Considering the results obtained in their research, together with those obtained by previous investigators, Lamb and Eliassen (91) postulated the following hypothesis concerning the possible mechanisms of corrosion inhibition by phosphate glass. Metaphosphate in solution reacts with the corrosion products in the vicinity of the anodes resulting in the formation of positively charged colloidal particles. These particles, containing iron oxides and metaphosphate, are subsequently deposited on the cathodes through electrodeposition. The formation of these particles are stimulated by the presence of divalent cations in solution. The film thus formed decreases the rate of corrosion of iron in water by increasing the degree of polarization of the cathodes in the corrosion cells. They noted a decrease in corrosion protection by phosphates at high pH values. The decrease in the amount of protective film deposited at high pH was possibly due to the increasing solubility of iron. They also found that the deposition of metaphosphate on the cathode was favored by reduction in the pH of the solution to a value of approximately 5.0.

Butler and Owen (92) have reported that the addition of

metaphosphate together with calcium ion (particularly at higher concentrations) is capable of reducing corrosion rates in water containing large amounts of sodium chloride. In the absence of calcium ion, it was found that small amounts of metaphosphate stimulated corrosion by an amount depending upon the chloride ion concentration. However, in the absence of calcium ion, further increasing the metaphosphate concentration above a certain critical amount produced a decrease in the corrosion rate. Moreover, efficient inhibition was obtained when a sufficient amount of both metaphosphate and calcium ion were present, the critical requirement of metaphosphate decreasing with increasing calcium ion concentration. This may have been due to the change of solubility of the phosphate complex due to the presence of calcium ion.

Butler and Owen (92) also found that pH values, at the end of batch corrosion tests involving the addition of phosphate, were several units higher than at the start of the test. They also reported that the pH value at the end of the tests gave some indication as to whether corrosion inhibition had occurred by phosphate treatment. It is not clear why they observed that inhibitor solutions exhibit final pH values in the range 6.0 to 7.5 and are lower than final pH values of other non-inhibiting solutions.

The changes in pH during the test may be linked to the reduction of metaphosphate concentration either in forming a protective film, whereby the pH remains high, or by degradation to the orthophosphate, whereby the pH becomes lower. In addition, the reversion to the orthophosphate is slowed down when effective inhibition has been achieved.

Stumm and Morgan (93) constructed solubility diagrams of various forms as shown in Figure 94 which shows a plot of P_T (Soluble phosphate as P) in equilibrium with solid $Ca_5(OH)(PO_4)_3$ and $CaHPO_4$ at the various concentrations of calcium ions. It was observed that soluble phosphate was controlled by $Ca_5(OH)(PO_4)_3$ in natural waters (pH = 7.5) when some calcium ion is present. Figure 94 also shows that a calcium ion level of 100 mg/l lowers the maximum equilibrium P_T to 1 $\mu\text{g/l}$. Therefore, it appears that hydroxylapatite, $Ca_5(OH)(PO_4)_3$, should be considered as a likely stable solid phase in natural waters. From these results, it appears likely that, in the presence of calcium ion, metaphosphate reacts with calcium ion to form an insoluble protective film.

In addition, Lahodny-Sarc and Kastelan (94) have reported that, in the presence of calcium ion, metaphosphate reacted with calcium ion and formed a glass-like film which deposited on cathodic areas of metal surface thereby increasing cathodic polarization. Therefore, the corrosion of mild steel can be

effectively reduced by the addition of a certain critical amount of hydroxide in the presence of divalent cations, such as calcium ion.

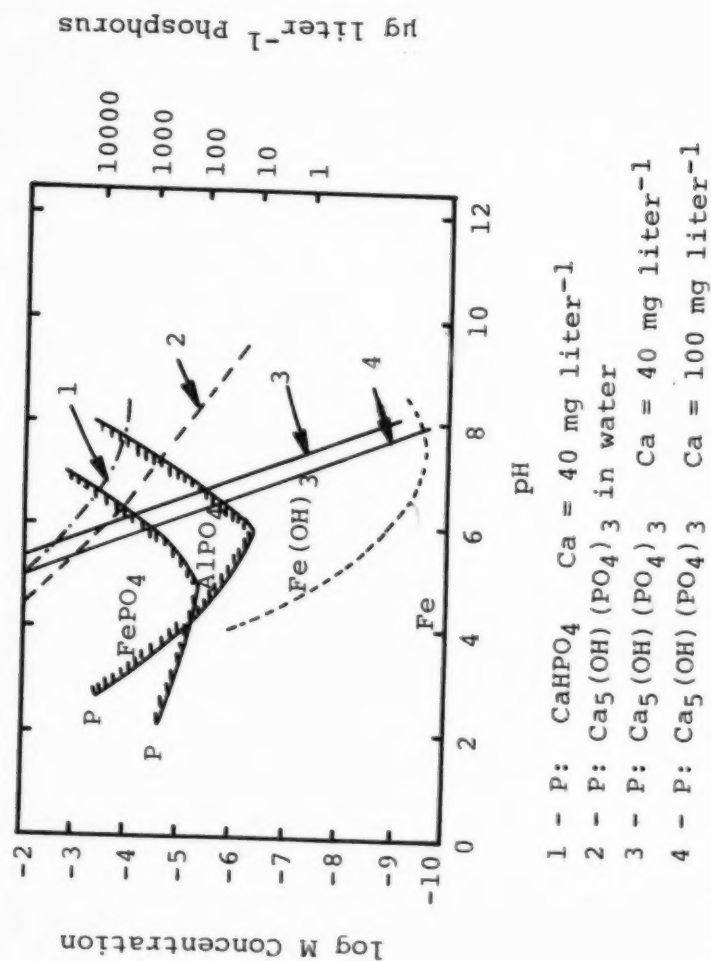


Fig. 94 Effect of pH on Various Phosphate Forms After Stumm and Morgan (93)

effectively reduced by the addition of a certain critical amount of metaphosphate in the presence of divalent cations, such as calcium ion.

APPENDIX B
SURVEY QUESTIONNAIRE

April 11, 1977

WATER UTILITY MANAGERS AND WATER SUPPLY ENGINEERS

RE: SURVEY OF WATER QUALITY PROBLEMS IN DISTRIBUTION SYSTEMS

Dear Sir:

Several years ago the AWWA Research Foundation conducted a survey of water utility managers to determine research needs in the water utilities industry. The results of that survey indicated that many utility managers felt that the deterioration of water quality in the distribution system was their most pressing and nagging problem. The results of the survey were announced in the Journal.

We at the University of Missouri in Columbia, in cooperation with the AWWA Research Foundation, are attempting to compile some field information on the extent and cause of water quality deterioration in distribution systems. This project has been funded by a research grant from the U.S. Environmental Protection Agency. One of the objectives of this study is to obtain information about distribution systems nation wide. It is our hope that we can obtain the cooperation of the leading water utilities managers and water supply engineers in filling out the enclosed survey questionnaire. We would appreciate it if you would complete and return this questionnaire.

In many instances, we realize that the information requested may not be available. In such cases the most accurate estimates available would be appreciated. We thank you for your cooperation in supporting this research effort. We hope that ultimately this coordinated research will lead to better water quality throughout America.

Sincerely yours,

John T. O'Connor

John T. O'Connor
Professor and Chairman
Department of Civil Engineering

QUESTIONNAIRE FOR WATER UTILITY MANAGERS:
WATER QUALITY PROBLEMS IN DISTRIBUTION SYSTEMS

(Please check appropriate space (s))

A. Utility Information:

1. Please state the complete name and location of the water utility
_____ (city or country) _____ State.
2. Is the water utility
 - a. Privately owned _____
 - b. City or County owned _____
 - c. State or Federally owned _____
 - d. Other (please specify) _____
3. The approximate average flow to the water distribution system is _____ mgd, but the rated capacity of the treatment facility is _____ mgd.
4. Approximately how many consumers are served by your water utility? _____.

B. Raw & Finished Water Information

1. Raw water source is

well or ground water _____	surface: lake or impoundment _____
surface: river water _____	other (please specify) _____
2. List the average raw and finished water quality and indicate levels, if available, in mg/l (except pH, turbidity and bacterial counts). If the parameter is not measured, please indicate by marking "NM". Also, please check the appropriate column which best represents the seasonal variability of your raw water source.

	Raw	Finished	Seasonal Variability		
			slight	moderate	large
Turbidity	_____	_____	_____	_____	_____
pH	_____	_____	_____	_____	_____
Iron	_____	_____	_____	_____	_____
Manganese	_____	_____	_____	_____	_____
Calcium	_____	_____	_____	_____	_____
Magnesium	_____	_____	_____	_____	_____
Sodium	_____	_____	_____	_____	_____
Ammonia-N	_____	_____	_____	_____	_____
Hardness, as CaCO ₃	_____	_____	_____	_____	_____
Alkalinity, as CaCO ₃	_____	_____	_____	_____	_____
Sulfate	_____	_____	_____	_____	_____
Chloride	_____	_____	_____	_____	_____
Hydrogen Sulfide	_____	_____	_____	_____	_____
Nitrate	_____	_____	_____	_____	_____
Phosphate	_____	_____	_____	_____	_____
Dissolved Oxygen	_____	_____	_____	_____	_____
Temperature Range	_____	_____	_____	_____	_____
Total Solids	_____	_____	_____	_____	_____
Total Organic Carbon	_____	_____	_____	_____	_____
Total Coliform	_____	_____	_____	_____	_____
Fecal Coliform	_____	_____	_____	_____	_____
Total Plate Count	_____	_____	_____	_____	_____

C. Water Treatment Process Information

1. Please check the unit processes employed in the water treatment.

Pretreatment

Aeration	_____
Presedimentation	_____
Coagulation/Flocculation	_____
Sedimentation	_____
Pre-Chlorination	_____
Permanganate Oxidation	_____

Softening

Lime _____
Excess Lime _____
Split Treatment _____
Lime-Soda Ash _____
Ion Exchange _____
Recarbonation _____

Filtration

Sand (Granular media) _____
Diatomaceous Earth _____
Direct Filtration _____

Carbon Treatment

Powdered	_____
Granular	_____

Disinfection

Chlorine _____
Chloramine _____
Ozone _____

Post Treatment

pH Adjustment _____
Fluoridation _____
Phosphate Addition _____
Ammonia Addition _____

None

Others (please specify)

2. Check the chemicals routinely (R) or occasionally (O) used in treating the water.

	R	O		R	O		R	O
Alum	_____	_____	Ferric Chloride	_____	_____	Chlorine	_____	_____
Lime	_____	_____	Sodium aluminate	_____	_____	Calcium hypochlorite	_____	_____
Soda Ash	_____	_____	(Soda alum)	_____	_____	Chlorine dioxide	_____	_____
Ferric Sulfate	_____	_____	Sodium silicate	_____	_____	Ozone	_____	_____
(ferrifloc)	_____	_____	(water glass)	_____	_____	Sulfur dioxide	_____	_____
Ferrous Sulfate	_____	_____	Ammonium sulfate	_____	_____	Bentonite clay	_____	_____
(copperas)	_____	_____	Anhydrous ammonia	_____	_____	Carbon dioxide	_____	_____
	R	O		R	O		R	O
Activated carbon	_____	_____	Hydrofluosilicic Acid	_____	_____			
Sodium sulfite	_____	_____	Sodium fluoride	_____	_____			
Hydrochloric Acid	_____	_____	Sodium silicofluoride	_____	_____			
Sulfuric Acid	_____	_____	Activated alumina	_____	_____			
Sodium Hydroxide	_____	_____	Potassium permanganate	_____	_____			
Polyphosphate	_____	_____	Others, please specify	_____	_____			

3. Please list the average chlorine residuals generally maintained:

	Plant Effluent	Distribution System
a. Free Chlorine, mg/l	_____	_____
b. Combined Chlorine, mg/l	_____	_____
c. Total Chlorine, mg/l	_____	_____

D. Water Distribution System Information:

1. List the approximate year the distribution system was initially laid, as well as the year of any major additions or revisions.

Initial _____ Additions _____

2. Please check which of the following types of pipe are used, as well as the approximate relative percentage of each, in your distribution system:

	Yes	%		Yes	%
A. Cast Iron, uncoated	_____	_____	F. Polyvinyl Chloride	_____	_____
B. Cast Iron, cement lined	_____	_____	G. Concrete	_____	_____
C. Cast Iron, asphalt lined	_____	_____	H. Copper	_____	_____
D. Galvanized Iron	_____	_____	I. Other (specify)	_____	_____
E. Cement Asbestos	_____	_____			

E. Distribution System Water Quality Problems

1. Does the water utility maintain records of consumer complaints regarding water quality?
Yes _____ No _____. If yes, approximately how many years have such records been kept? _____

2. Approximately how many consumer complaints are received
monthly? _____ yearly? _____

3. Are the consumer complaints seasonal? Yes _____ No _____.
If yes, which months? _____

4. Please indicate which of the following consumer complaints are received, as well as the relative percentage of the total number of complaints:

	Occur?	% of Total
a. Taste	_____	_____
b. Odor	_____	_____
c. Cloudiness or Turbidity	_____	_____
d. "Red" water or plumbing	_____	_____
e. "Black" water or plumbing	_____	_____
f. Other, please specify	_____	_____
_____	_____	_____
_____	_____	_____

5. Are most of the consumer complaints located in one area of the municipality or distributed throughout the system?

One area _____ Distributed _____

6. Are most of the water quality problems reported in "dead end" areas of the distribution system? Yes _____ No _____

7. What is the approximate age of the distribution system in trouble areas? _____ years.
What is the composition of pipes in these areas? _____

8. Please check which of the following bacteriological tests are undertaken in examining water quality problem areas. Also, check any test which has shown positive microbial activity.

	Measured?	Positive?
Total plate count	_____	_____
Total Coliform	_____	_____
Fecal Coliform	_____	_____
Iron Bacteria	_____	_____
Actinomyces	_____	_____
Others, please specify	_____	_____

9. Are records maintained of the bacteriological tests performed?

Yes _____ No _____. If yes, please indicate the number of years of records available _____

10. Please check any parameters which are monitored in trouble areas:

- | | | | |
|-----------------------------|-------|---------------------------|-------|
| a. turbidity | _____ | g. Taste and Odor | _____ |
| b. pH | _____ | h. Dissolved Oxygen | _____ |
| c. Cl ₂ Residual | _____ | i. SO ₄ or S | _____ |
| d. Fe | _____ | j. Organic N | _____ |
| e. Mn | _____ | k. Organic C | _____ |
| f. H ₂ S | _____ | l. Others, please specify | _____ |

11. List any of the above water quality parameters which undergo an unexpected change in the distribution system in problem areas. What water quality problem is associated with these changes?

12. Are the Cl₂ residuals being maintained in water quality problem areas? Yes _____ No _____
If no, what is the Cl₂ residual in these trouble areas? _____ mg/l.

13. Are storage facilities employed in the distribution system? Yes _____ No _____
If yes, does there appear to be any close correlation between the location of storage facilities and areas of water quality problems? Yes _____ No _____

14. Please check and rank whichever of the following remedial measures are used to control water quality problems?

- | | |
|--|-------|
| a. Main flushing | _____ |
| b. Increased Cl ₂ residual in trouble areas after complaint | _____ |
| c. Cl ₂ residual reinforcement throughout the system | _____ |
| d. Sacrificial anodes | _____ |
| e. Other, please specify | _____ |

15. Of the above mentioned remedial measures, which do you find most useful in combating water quality problems in the distribution system? _____

16. If main flushing is used, what is the approximate time between successive flushings?

- | | | | |
|---------------|-------|--------------------------|-------|
| a. Weekly | _____ | e. Quarterly | _____ |
| b. Bi-weekly | _____ | f. 6 months | _____ |
| c. Monthly | _____ | g. Yearly | _____ |
| d. Bi-monthly | _____ | h. Other, please specify | _____ |

17. If possible, please estimate the total annual cost of these remedial measures _____

18. Have algae been detected in the distribution system? Yes _____ No _____
If yes, are they found throughout the system or more often found near reported trouble areas?

- | | | | |
|------------|-------|-----------------------|-------|
| a. Uniform | _____ | b. Trouble areas only | _____ |
|------------|-------|-----------------------|-------|

19. Please relate any other specialized distribution system problems which occur in your distribution system. _____

20. Would your water utility be willing to cooperate in a research program directed at remedying water quality problems in the distribution system? Yes _____ No _____

21. Name and mailing address of survey respondent: _____

Thank you for your time and cooperation

APPENDIX C

The following are descriptions of commercial phosphate products used as corrosion control agents in water distribution systems and which were used in this investigation. These include: Calgon Corporation products, C-39 and TG-10, Olin Corporation's sodium hexametaphosphate (SHMP) and Monsanto Industrial Chemicals' sodium hexametaphosphate. Among these phosphate compounds, Calgon's C-39 and TG-10 contain 55-60% P_2O_5 and 9.5-11% ZnO fused into plates. Olin's SHMP contains 67.8% P_2O_5 and 31.5% Na_2O . Monsanto's SHMP contains 67.4% P_2O_5 and 32.4% Na_2O .

MANUFACTURER'S DESCRIPTION OF CALGON C-39

Calgon C-39 Corrosion and Scale Inhibitor is a readily soluble, highly stable, fused phosphate-zinc glass supplied in the form of clear glassy platelets. It is marketed to control corrosion and scale formation in municipal water systems and industrial service water or cooling water systems.

Purposes

When added continuously at low dosages to flowing water, C-39 forms a film of molecular dimensions on ferrous metal surfaces in the system. The film laid down by electro-deposition at local cathodic areas to stifle the corrosion reaction, overcomes red water and tuberculation. It also stabilizes scale forming water so that calcium carbonate does not deposit.

Being a phosphate-zinc glass, C-39 rapidly forms a protective film that is superior to that formed by other phosphates in preventing corrosion.

Advantages

- Corrosion inhibition by cathodic action overcomes red water and tuberculation problems in water supply systems.
- Protective film is rapidly formed.
- Protective film does not inhibit heat transfer.
- Inhibits calcium carbonate and calcium sulfate scales (threshold stabilization).

- More effective at lower dosages than ordinary sodium phosphate glass or crystalline products.
- More resistant to enzymatic reversion to orthophosphate than sodium phosphate products.
- Feed solutions can be prepared over a wide range of water temperatures and dissolved solids content.
- Can be used to treat potable water supplies.

Feed Requirements

Generally, feed rates for treating service or cooling water will be in the range between 1 and 10 mg/l. Optimum dosage will depend on the type of system, water velocity, temperature, pH and the concentration and nature of solids that are encountered. Feed solutions of C-39 are more quickly prepared and are the most stable among those using a fused glassy phosphate. A Calgon Corporation water conditioning specialist is available to recommend a treatment program, including the initial feed rate.

For municipal, low temperature potable and industrial service water systems, a feed rate of 1 to 3 mg/l C-39 is effective.

For industrial once-through cooling systems a feed rate of 3 to 5 mg/l C-39 is effective.

Open recirculating systems generally require 5 to 10 mg/l.

In municipal systems, pH control is generally unnecessary. However, in industrial once-through cooling systems the pH should be maintained between 6.7 and 7.5 for maximum benefit. In open recirculating systems which concentrate by evaporation, a pH control in the range from 6.8 to 7.5 is desirable. Lower pH's can be used even in copper-containing systems when treatment is supplemented with a copper corrosion inhibitor such as Calgon's CL-56.

Methods of Feeding

Stock feed solutions up to 1.5 pounds per gallon can be prepared in soft waters by means of a dissolving tank with basket and an agitator. The solution should be fed by a corrosion resistant chemical feed pump. Stock solutions are usually stable for several days.

Specifications

Appearance.....clear glassy platelets
pH of 1% solution.....7.5 to 8.5
Solubility in water.....up to 1.5 lbs. per gallon
Odor.....none
Particle size.....100% through U.S. Coarse 2" Sieve
5% through U.S. Coarse 0.5" Sieve

MANUFACTURER'S DESCRIPTION OF TG-10

Calgon Composition TG-10 is a highly stable, fused zinc-phosphate glass in plate form.

Purpose

Composition TG-10 is used to control corrosion, scale and red water in municipal and industrial service water systems and in industrial cooling water systems. When added continuously to flowing water at low dosage rates, it quickly forms a protective zinc-fortified phosphate film on all metal surfaces contacted by the treated water. This film is superior to that formed by sodium hexametaphosphate, particularly when conditions are critical with respect to pH, flow rate and temperature, or where rapid film formation is important. Composition TG-10 is also more effective than any physical mixture of sodium polyphosphate and zinc salts.

Use of Composition TG-10 is especially valuable in conjunction with mechanical cleaning of water mains where a protective phosphate film must be formed rapidly on freshly exposed metal in order to maintain high flow coefficients. A high concentration of Composition TG-10 at this stage helps disperse existing corrosion products, making it easier to flush them from the system. Rapid film deposition also helps eliminate "red water" complaints which often result when mains are returned to service.

Advantages

- Can be used to treat potable water supplies.
- Protective film forms rapidly - ideal for use in conjunction with mechanical cleaning of water mains.
- Inhibits calcium carbonate and calcium sulfate scales.
- Stabilizes dissolved iron and manganese.

- More effective at low dosage than sodium phosphate glass or physical-mix products.
- More resistant to enzymatic reversion than sodium phosphate products.
- Feed solutions can be prepared easily over a wide range of water temperatures and dissolved solids levels.

Feed Requirements

Feed requirements will vary depending on the type of system and specific water conditions such as velocity, temperature, pH and the concentration and nature of dissolved solids present. Your Calgon representative will provide technical assistance in determining optimum dosage and method of feeding based on your individual system conditions and requirements.

Generally, the following feed rates will provide effective treatment:

Municipal, potable and industrial service water systems -
0.5 - 3.0 ppm

Industrial once-through cooling water systems - 0.5 -
5.0 ppm

Open recirculating cooling water systems - 10 - 20 ppm

In open recirculating systems which concentrate by evaporation, a pH range of 6.8 to 7.2 is recommended. When operating at lower pH ranges, Calgon TG-10 treatment should be supplemented with Calgon CL-56 Corrosion Inhibitor to protect copper in the system.

When treating newly cleaned mains, a dosage of 10 ppm should be applied to the water for one week before resuming normal feed rate of 0.5 to 3 ppm. If a 10-ppm dosage cannot be provided by a booster feed to the isolated main, dosage should be increased in the entire system.

MANUFACTURER'S DESCRIPTION OF OLIN SODIUM HEXAMETAPHOSPHATE Polyphos' (Sodium Hexametaphosphate)

Polyphos is the Olin trade name for a water soluble, glassy sodium polyphosphate. Glassy phosphates are commonly referred to as metaphosphate or hexametaphosphate. Polyphos is available in a variety of grades including powdered, ground, plate (1/8" to 1/4" thick x 1"), and lump. The lump grade

is available in two sizes - walnut size (3/8" x 3/4") and pea size (1/4" x 1/2").

Composition

An infinite number of true glassy sodium polyphosphates can be formed within the molar range of 1 Na₂O/1 P₂O₅ to 1.34 Na₂O/1 P₂O₅. The chemical, physical and structural properties of these glasses are of such similarity that in practical utility, one may be substituted for another. Polyphos has a molar composition of 1.1 Na₂O₅ which is in the high P₂O₅ end of the glass-forming range.

Principal Uses

Industrial and municipal water treatment

Scale formation prevention

Iron precipitation prevention

Corrosion control

Boiler water compounds

Dishwashing and detergent compounds

Textile processing and dyeing

Leather tanning

Viscosity control of oil well drilling muds

Clay purification by deflocculation

Flotation and desliming of minerals

Pigment dispersion

Paper processing

Food processing

Typical Analysis

Phosphorus pentoxide, P ₂ O ₅ (%).....	67.8
Sodium oxide, Na ₂ O (%).....	31.5

Typical Properties

pH, 1% solution.....	6.8
Density (lb/ft ³)	
ground.....	84
plate.....	80
lump, walnut size.....	87
lump, pea size.....	87
powdered.....	70

Properties

Solubility. Polyphos is highly soluble. At 23.8°C, 100 grams of water will readily dissolve more than 150 grams of Polyphos.

Inhibition. Minute quantities of Polyphos inhibit precipitation of calcium and magnesium salts in hard water.

Sequestration and Water Softening. Larger amounts of Polyphos, when added to hard water, prevent the precipitation (sequestration) of calcium and magnesium salts by forming soluble complexes with these elements. Precipitated hardness will re-dissolve. In sequestration, the calcium and magnesium ions are held so firmly in soluble chemical combination that they will not react with soap (added or formed by saponification of greases and oils) during the cleaning operation. Calcium and magnesium soap curds which become enmeshed in fabrics or stick to cleaning equipment are avoided. Polyphos also forms inert complexes with certain metallic ions such as iron, copper, nickel, manganese and zinc.

Dispersion. Another very useful property of Polyphos is its ability to deflocculate and suspend materials insoluble in water such as clay dispersions for the coating of paper.

Stability. Since Polyphos is used mainly in aqueous solutions, a knowledge of the stability of these solutions is very important. Glasses with a molar ratio of 1.1 Na₂O/1 P₂O₅, or less, are acidic in nature and eventually revert to orthophosphates in water.

MANUFACTURER'S DESCRIPTION OF MONSANTO SODIUM HEXAMETAPHOSPHATE
Product: Sodium Hexametaphosphate (SHMP) Technical Grade

General Description

A glassy, amorphous sodium polyphosphate with molar Na/P approximately 1.1. Meets AWWA Standard.

Formula

(Avg.) Na₁₈P₁₆O₄₉

Molecular Weight

Avg. 1694

Appearance

Plates, Code 310.....Clean, clear, glass plates
Powder, Code 320.....Clean, coarse white powder
Crushed, Code 340.....A white, coarse granular material
% P_2O_5 66.5 Minimum
Sizing, Plates.....<4 Inches

Typical Values

% P_2O_5 67.4
% Total Na_2O 32.4
% Alkalinity as Na_2O 3.0
% Loss on Ignition.....0.5
% Water Insoluble.....0.05
pH, 1% Solution.....6.9

Handling Precautions

No precaution statement needed. This material appears to possess no toxicological properties which would require special handling other than the good hygienic practices employed with any industrial chemical.

Uses

SHMP has many industrial uses, including sequestration of metallic ions, deflocculation of slurries, textile cleaning, and metal cleaning. It has consumer product applications in laundry aids and bath beads.